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The use of sphere gaps at radio frequencies.

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USE OF SPHERE GAPS AT RADIO FREQUENCIES

BY

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INTRODUCTION

The sphere gap has for many years been an accepted method for the measurement of high voltage at power frequencies[1,2] and also for impulse testing. It is not however, at present an accepted standard for the measurement of high voltages at radio frequencies. This is largely due to the lack of published data on the spark-over values of sphere gaps in air at radio frequencies. There has been some work published in this field[3,4,5,6], but the results are not altogether consistent and the spectrum of frequencies covered is far from complete.

The purpose of this study is to evaluate the possibility of using sphere gaps for the measurement of moderately high voltages, - up to 20 kilovolts peak -, in the frequency range from 500 kilocycles to 15 megacycles. To accomplish this, a peak-reading vacuum-tube voltmeter, with associated capacitance-divider, was constructed and calibrated, and employed to determine the spark-over values of sphere gaps in air at these frequencies.

The results indicate that the sphere gap, if irradiated, may be used for the measurement of voltages in the ranges of magnitude and frequency considered. Consistent results show a break-down strength for air, at these frequencies, which is 80-85% of that at power frequencies. This is in general

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(1,2) For numbered references see bibliography.

agreement with the somewhat meagre data that has been published. [3,4,5,6] The results are shown in the curves, pages 28 to 33.

The possibility of using a rod gap was also investigated. These results are less encouraging, and are shown in the curves, pages 34 to 37.

THE SPHERE GAP AS A VOLTAGE-MEASURING INSTRUMENT

Use of Sphere Gaps at Power Frequencies:

The measurement of very high voltages, at power frequencies, can be accomplished readily and with considerable accuracy by the use of sphere gaps. The American Standards Association publication C 68.1 - 1942[1], sponsored by the American Institute of Electrical Engineers, gives tabulated values of spark-over voltage in air, for spheres of various diameters and spacings. Voltages up to 2,000 kilovolts peak are covered. A simple correction for air density must be made, because the dielectric strength of air is a function of its density. Within the range of air densities normally encountered near sea level, this variation is practically linear. The tabulated spark-over voltages are for the standard density conditions corresponding to a barometric pressure of 760 millimeters of mercury and a temperature of 25° Centigrade. According to this publication, no correction need be made for humidity, although there is some published data[7] indicating that humidity has a slight effect.

The axial field between spheres can be calculated [2,8], and with a knowledge of the break-down strength of air, the spark-over voltage for spheres of arbitrary diameter and specified gap spacing can therefore be calculated. The agreement between calculated and observed values is quite good[8], and enhances the use of sphere gaps for measuring voltage. It should be noted, however, that the sphere gap is a crest, or peak-reading device.

The field intensity along the axial line between the spheres is not uniform, being a maximum at the sphere surfaces and a minimum midway across the gap. Furthermore, if one sphere is grounded, which in practice is very often the case, the field intensity is somewhat distorted, placing greatest stress at the surface of the ungrounded sphere. However, these effects are not serious if the gap spacing is small compared to the sphere diameter. It is customary to choose spheres of sufficiently large diameter to fulfill this condition.

Although the gap spacing is quite critical in determining the spark-over voltage, the diameter of the spheres is not. For example, the 60-cycle crest voltages listed for a gap spacing of 1 cm. are 31,300 for 6.25 cm. spheres, and 31,700 for 12.5 cm. spheres.

The sphere-gap as a voltage-measuring device suffers the disadvantage that the breakdown of the gap imposes practically a short circuit on the voltage source being measured.

For this reason it is customary to connect a fairly high resistance in series with the gap.

Theory of Spark-over:

The generally accepted theory of the spark-over of a gap[9,10,11,12] postulates that electrons existing in the gap are attracted toward the anode, and if the field intensity is great enough, they acquire sufficient energy during the traverse of a mean-free-path to ionize an atom on collision. This produces more electrons, and an avalanche is formed, which is spear-headed toward the anode, and leaves in its trail a highly-ionized column of air. The velocity of this process has been studied by many investigators[9,18] and found to be of the order of 10^8 centimeters per second, which is greater than can be accounted for by the mobility of the electrons. Consequently it is believed that the ionized body of the avalanche emits light photons, some of which cause ionization in advance of the avalanche.[9] Spark-over occurs when this action completely bridges the gap.

Effects of Irradiation:

The initiation of the spark-over mechanism requires the existence of one or more electrons in the gap. There is therefore some uncertainty in the value of voltage at which a gap will spark over, unless the voltage is maintained for a reasonable time. In other words, there is an unpredictable time lag in the process. To reduce this uncertainty, it is often the practice to irradiate the sphere gap. using ultra-

violet light, X-rays, or emissions from radio-active materials. This guarantees a generous supply of electrons in the gap, reduces the spark-over time lag, and improves the consistency of the observed values of spark-over voltages. Irradiation generally lowers the spark-over values[7,13,14,15,16]. At power frequency, irradiation is usually considered necessary only for short gaps.

Use of Sphere Gaps for High Frequencies:

Some modification of practice and theory is needed when the sphere gap is used at high frequencies. In the first place, spheres of large diameter are unsuitable because of the charging current they would draw prior to spark over. For example, even 6.25 centimeter spheres spaced 0.5 centimeter apart would draw several amperes charging current at 10 megacycles with 10 Kv (rms) applied. Hence small spheres are practically necessary, and since sphere gaps cannot be employed with much reliability at gap spacings greater than the sphere diameter, it is evident that this limits their use, at high frequencies, to moderately high voltages. Also because of the appreciable charging currents, the use of high resistances in series with the gap will lead to inaccuracies.

Secondly, irradiation is more necessary at high frequencies. At 10 megacyles, a sine wave attains 95% or more of its crest value for only 10^{-8} second during each half-cycle. Hence time lags in the spark-over could lead to results much more erractic than those at power frequencies.

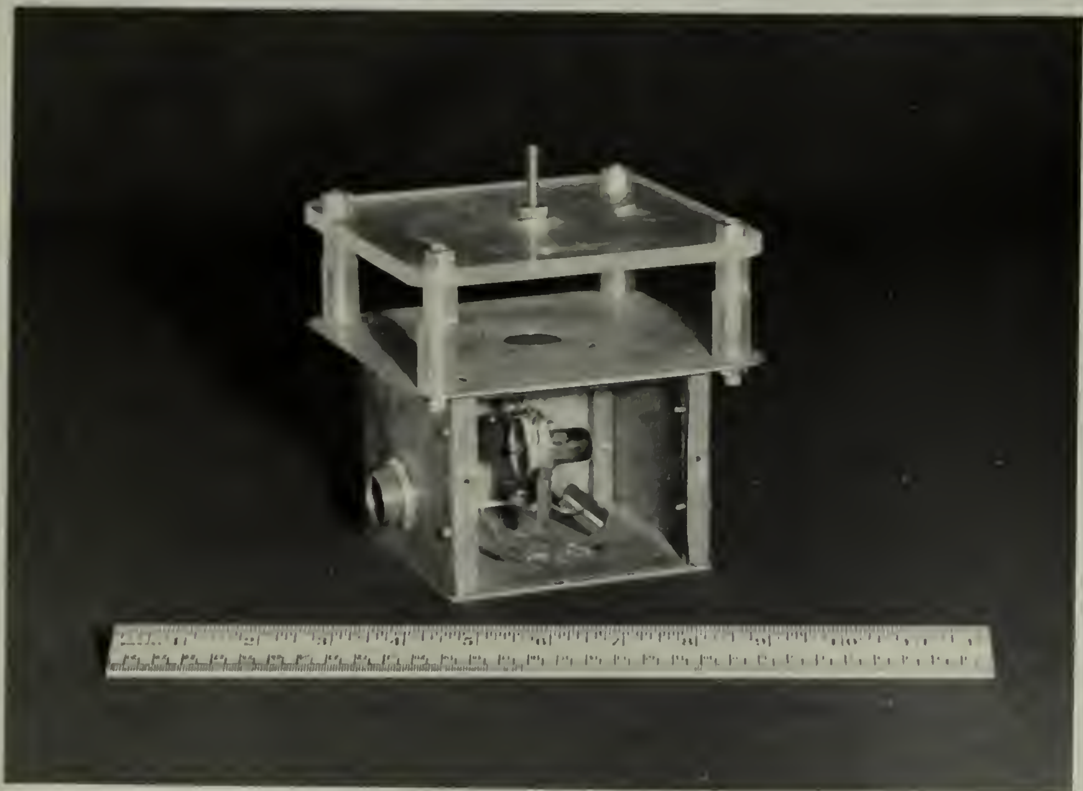
Theoretical studies indicate that the "avalanche" picture of the dielectric breakdown of a gas will hold so long as the electrons encounter many collisions per cycle of applied voltage.[21] But if the frequency and the gaseous pressure are such that the electrons experience many cycles of voltage between collisions, then a somewhat different theory of breakdown is postulated. The minimum dielectric strength of the gas occurs during transition from one situation to the other; that is, when an electron would experience about one collision per cycle of applied voltages. This minimum has been experimentally verified for gases at low pressures, using high frequency fields.[22,25] However, a rough calculation based on the classical value for the mean-free-path of an electron, indicates that for air at atmospheric pressure this minimum would occur at a frequency of the order of 10^{11} cycles per second. (See Appendix A). Hence theoretical considerations of spark-over in air, at radio frequencies or even at ultra-high frequencies, may be based on the "avalanche" theory outlined above.

EXPERIMENTAL WORK

The Vacuum-Tube Voltmeter:

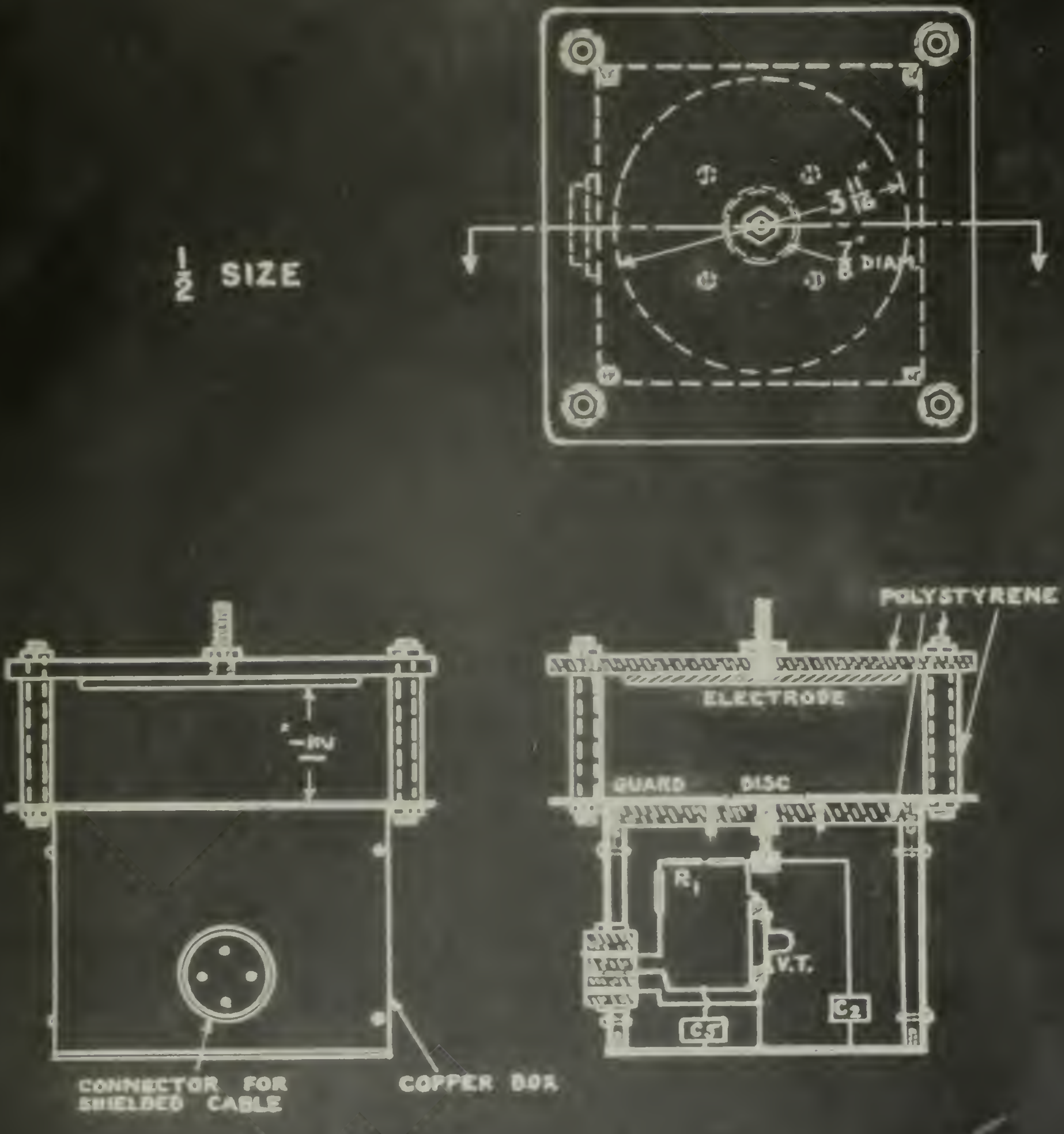
To test the performance of sphere gaps at high frequencies, it was first necessary to devise a suitable method for measuring accurately the voltages involved. For this purpose a vacuum-tube voltmeter with associated capacitance-divider was constructed. It is shown in the photograph on

page 7,



CAPACITANCE-DIVIDER VACUUM-TUBE VOLTMETER

In the lower view, one side of the shielding box is removed, to show inner construction.

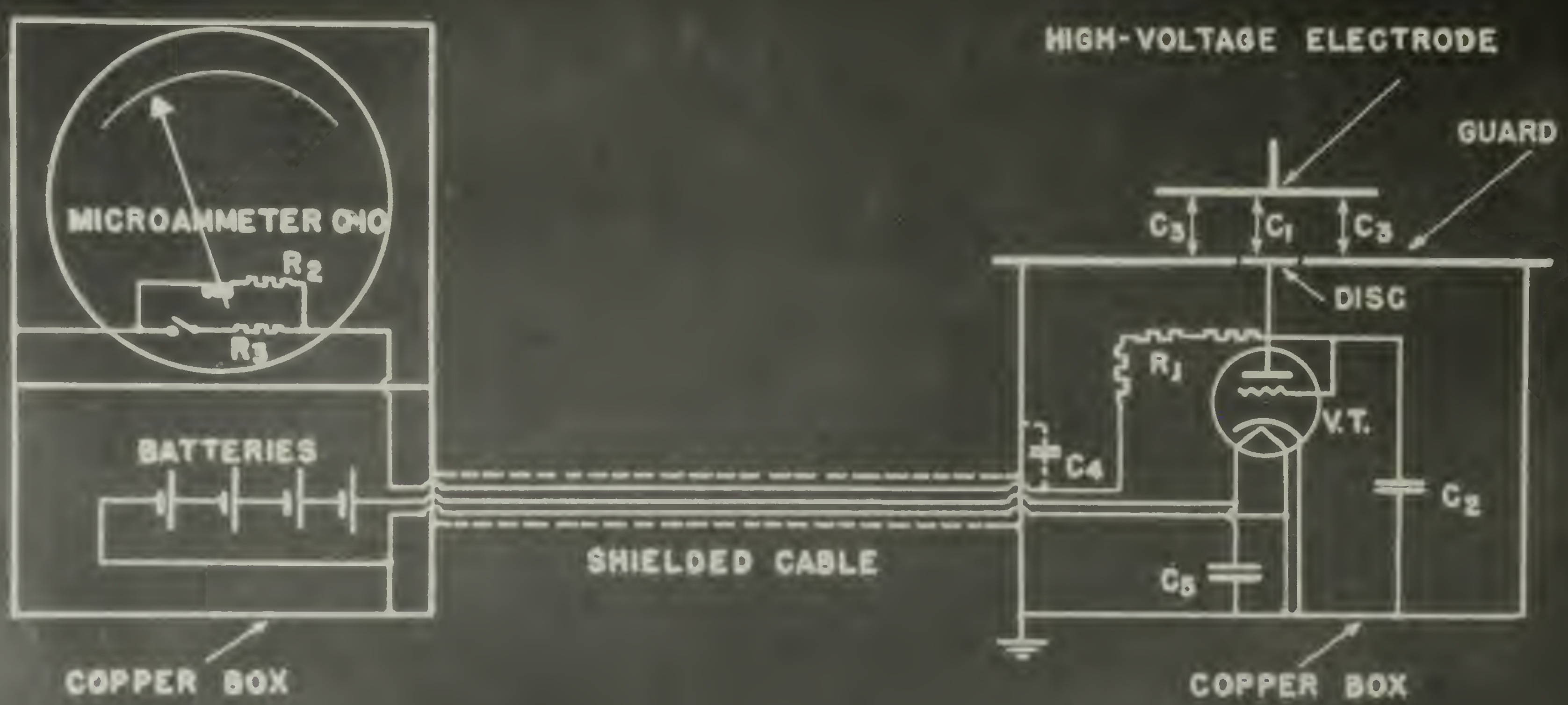


CAPACITANCE - DIVIDER

VACUUM - TUBE VOLTMETER

and by the drawings on page 8. The schematic circuit appears on page 10. The capacitance-divider comprises C_1 and C_2. C_1 is an air capacitance formed between the high-voltage electrode and the small disc, which is surrounded by a guard ring. The Value of C_1 is calculated from its dimensions to be $0.093\mu\mu$. F. C_2 consists of two small mica capacitors having nominal ratins of $5\mu\mu$F. and 20 $\mu\mu$F., connected in parallel, plus the capacitance to ground of the disc and the necessary connections. The value of C_2 was measured and found to be $33\mu\mu$F., over a range of frequencies from 500 kilocycles to 15 megacycles. C_3 is the capacitance formed by the high voltage electrode and the guard ring. It is about $5\mu\mu$F. C_4 represents the distributed capacitance to ground of 5 feet of shielded cable. It measures $335\mu\mu$F. C_5 is a $2000\mu\mu$F. by-pass capacitor.

The vacuum tube is a type 955 acorn tube, with grid and plate connected together, to form a diode rectifier. R_1 consists of three miniature type resistors in series, each rated at 1 megohm. These are type MPM resistors, manufactured by International Resistance Co. for high-frequency receivers and similar applications. At 500 kilocycles, the susceptance of C_2 is about 300 times the conductance of R_1 which parallels it, so the capacitance divider does not suffer frequency distortion in the range of frequencies considered. Furthermore, the time constant of R_1 C_2 is about 100 microseconds, permitting the voltage across C2, at 500 kilocycles, to average 99% of its peak value. Hence this capacitance-divider vacuum-



SCHEMATIC DIAGRAM OF CAPACITANCE-DIVIDER

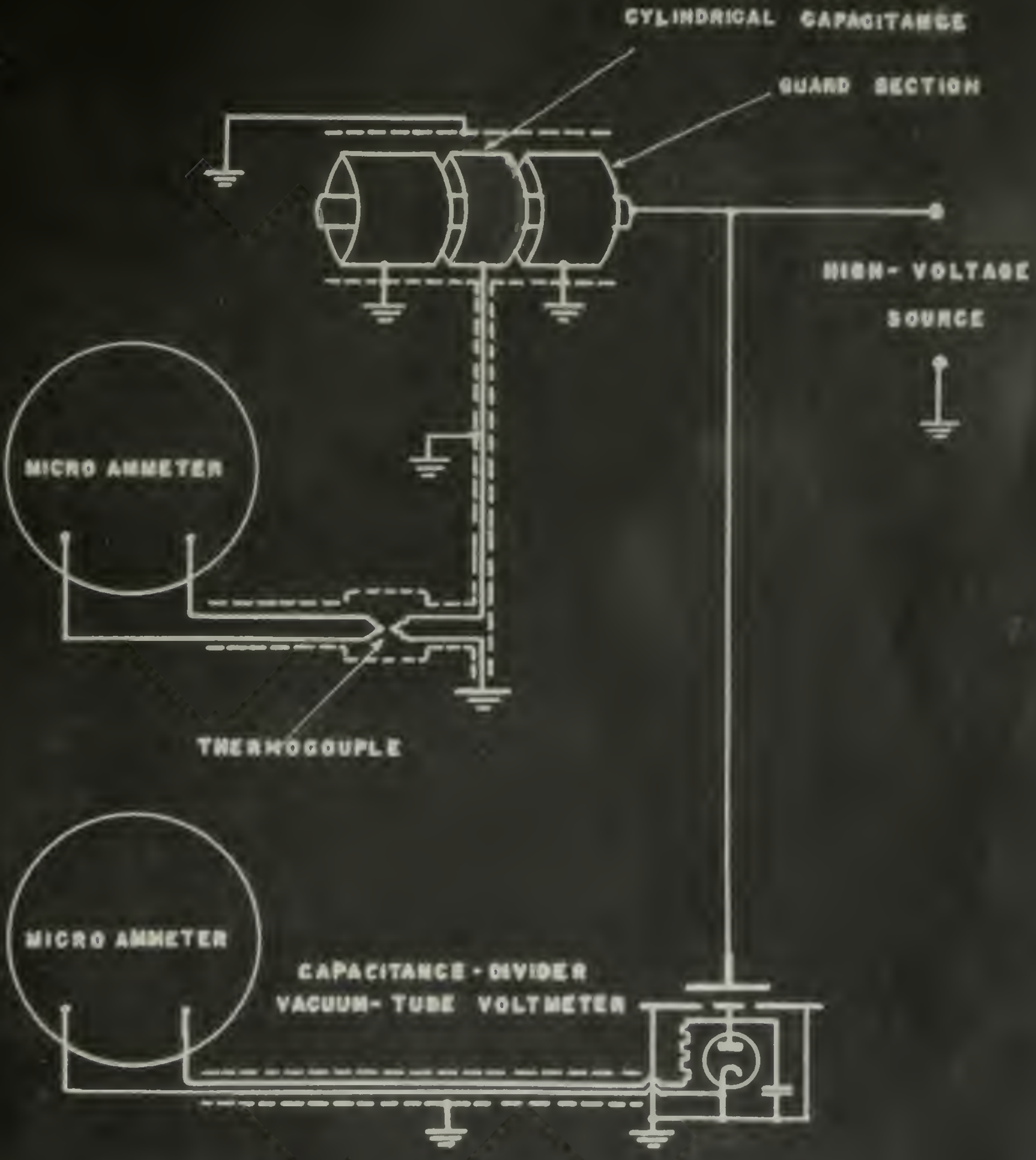
VACUUM-TUBE VOLTMETER

tube voltmeter should have a flat frequency response in the range of frequencies considered. This is borne out by the calibration date.

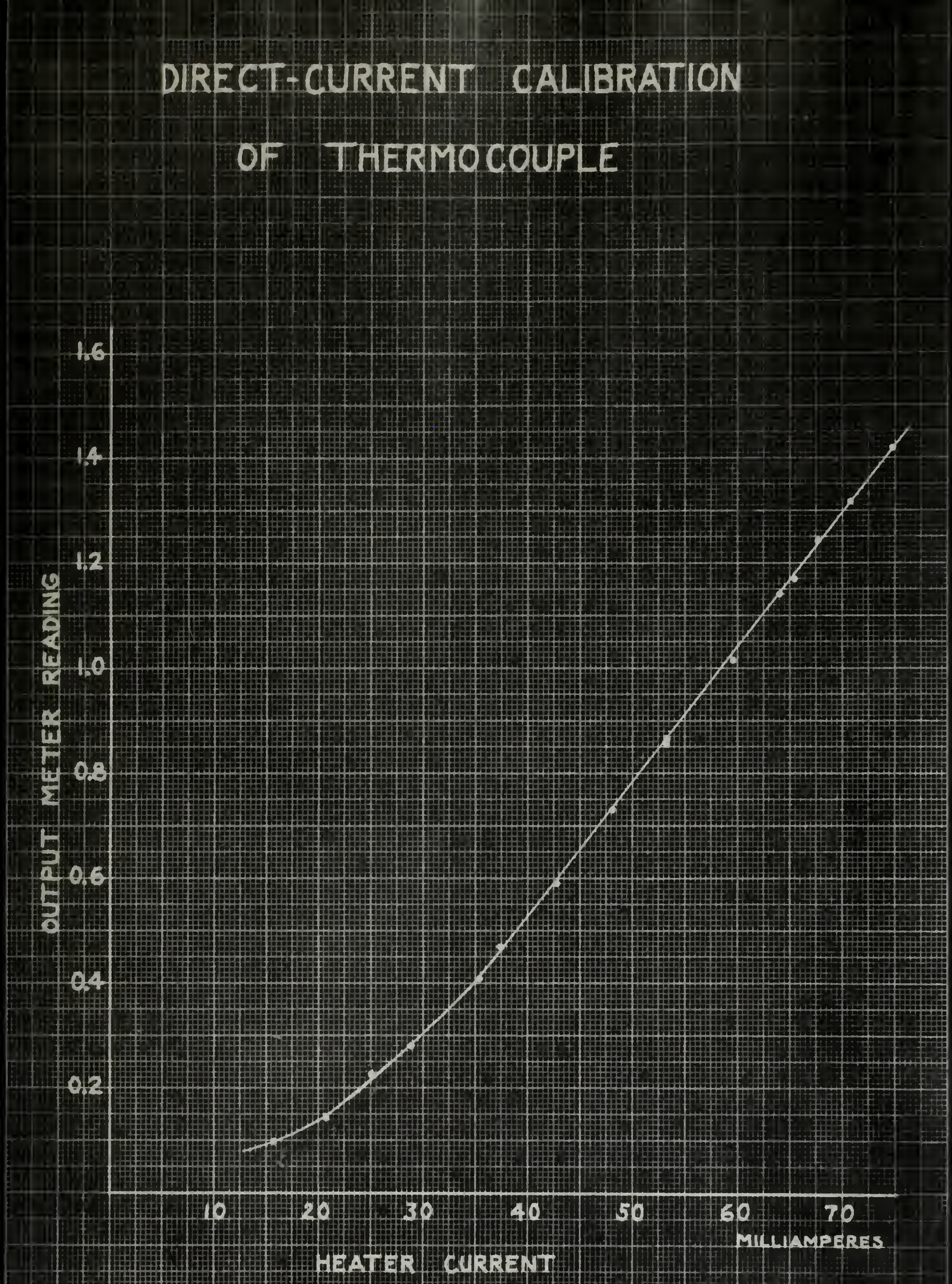
R_2 is the resistance of the microammeter, plus some wire-wound resistance units, and is 63.600 ohms. R_3 is a resistance of 40,100 ohms which can be shunted across the microammeter, thus increasing the range of the voltmeter by a factor of 2.62. The microammeter was originally a General Electric Co., type DP9, 0 to 3 voltmeter having 300,000 ohms resistance. Most of the internal resistance is removed, and it is used as a 0-10 microammeter. It has a scale length of 4 inches, with an accuracy of 1/2% of full scale. Four 1-1/2 volt flashlight cells are used for the vacuum-tube filament supply.

Calibration of Voltmeter:

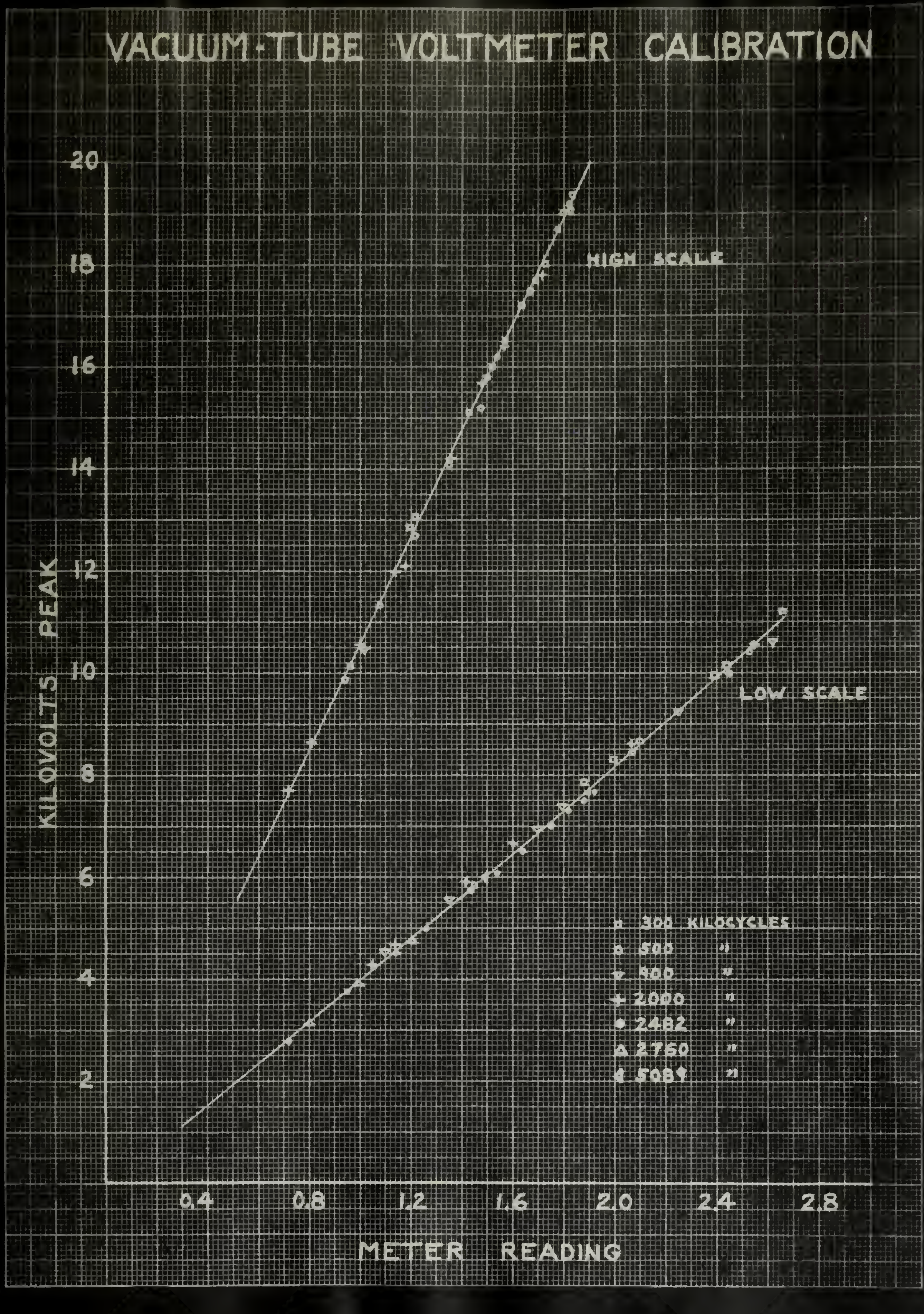
Calibration of the voltmeter over a considerable range of frequencies, was accomplished by simultaneous readings of the voltmeter and of the current drawn by a guard-ring type cylindrical capacitor, when these were both connected to the high voltage source. A schematic diagram of this set-up appears on page 12. The cylindrical capacitor current was measured by a thermocouple and associated microammeter, previously calibrated on direct current. The direct current calibration curve appears on page 13. The thermocouple is a Western Electric Co. vacuum type No. 5C having a nominal rating of 75 milliamperes and a heater resistance of 5 ohms.



SCHEMATIC DIAGRAM OF CALIBRATION CIRCUIT



DIRECT-CURRENT CALIBRATION
OF THERMOCOUPLE
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
OUTPUT METER READING
10
20
30
40
50
60
70
MILLIAMPERES
HEATER CURRENT

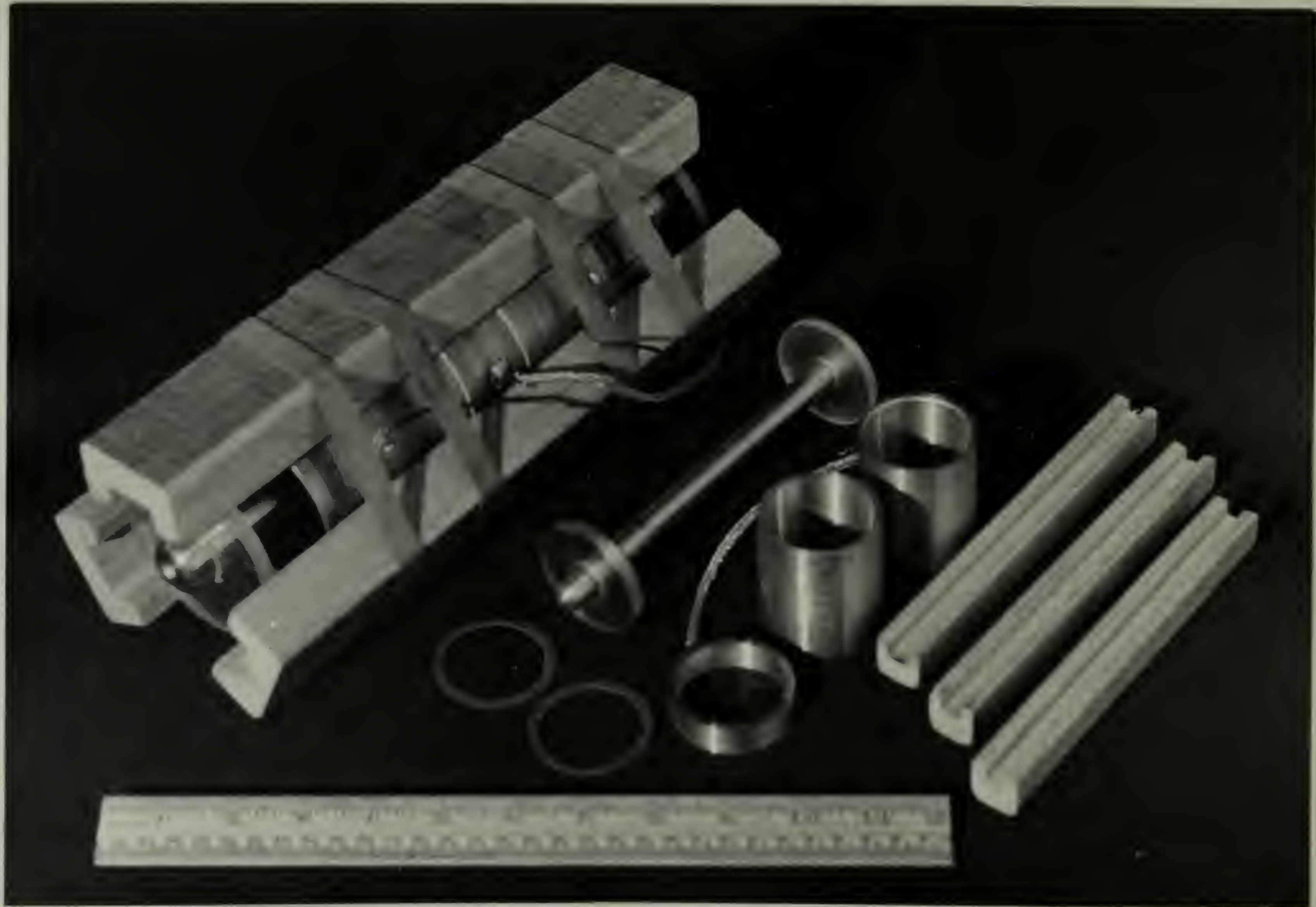

VACUUM-TUBE VOLTMETER CALIBRATION
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
HIGH SCALE
LOW SCALE
300 KILOCYCLES
500 "
900 "
2000 "
2482 "
2760 "
5089 "
0.4
0.8
1.2
1.6
2.0
2.4
2.8
METER READING

Its capacitance is about 2 $\mu\mu F$. and its inductance of the order of 0.05 microhenry.

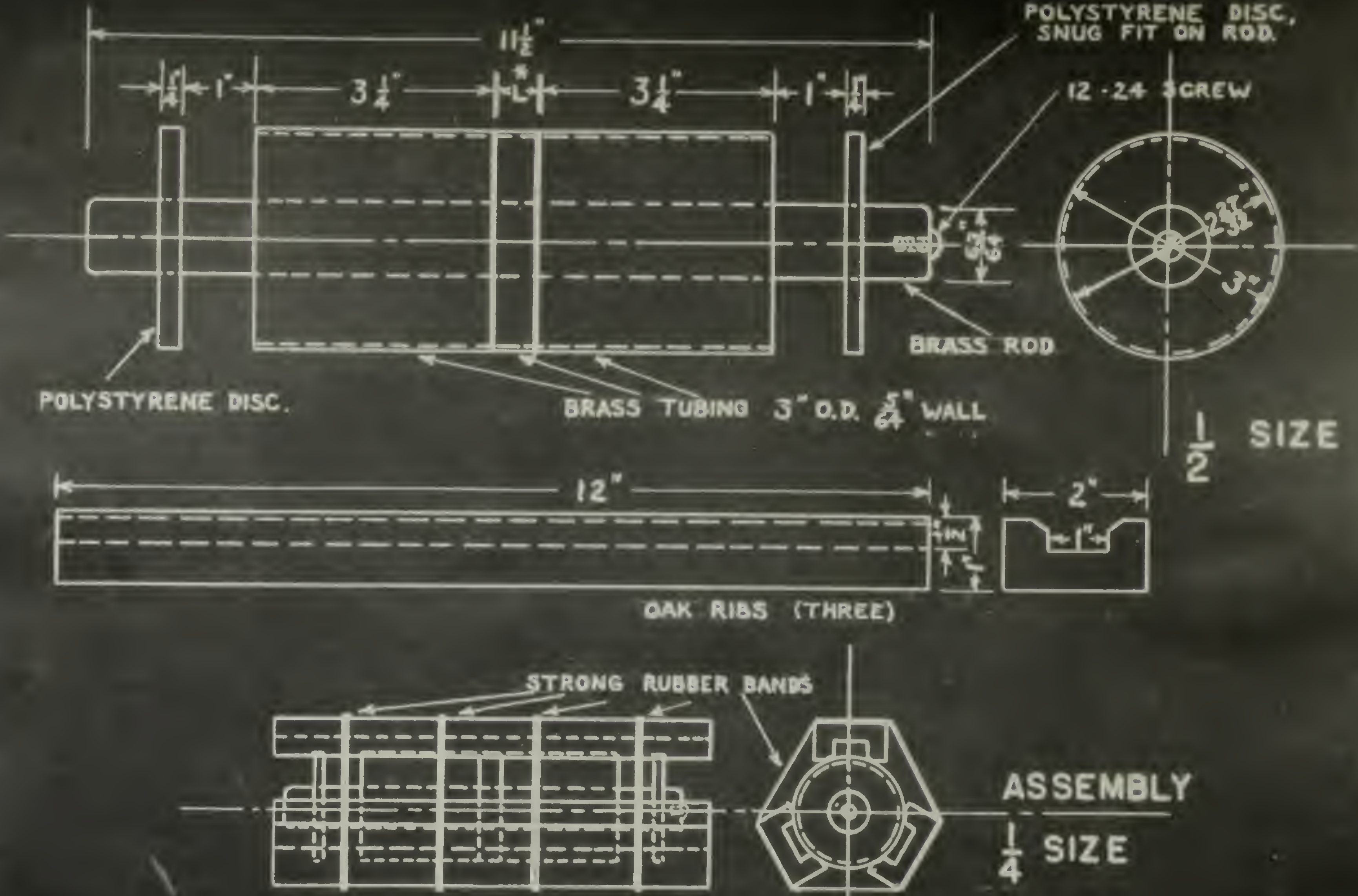
Two cylindrical capacitors were constructed. The second and larger one was built after the original one was found to be inadequate for voltages greater than 10 kilovolts peak. A photograph on page 16 shows these capacitors, and drawings of the larger one appear on page 17. For each capacitor, three interchangeable lengths of guarded outer cylinder were made, so that a wide range of voltage and frequency could be covered, while keeping the thermocouple current within its calibrated range. The resultant calibration of the capacitance-divider vacuum-tube voltmeter appears on page 14. The calibration is quite linear, and showed no variation with frequency in the range of frequencies, - 0.3 to 5 megacycles- over which it was calibrated.

Since the capacitor current read by means of the thermocouple is root-mean-square, while the voltmeter reads crest values, it was necessary to check the wave form during calibration. This was done by testing for harmonic content, using a General Radio Co. Precision Wavemeter type 724-A.

The thermocouple and cylindrical capacitor are not suitable for testing the sphere gaps directly, for several reasons. The first reason is that it is not a peak-reading arrangement, as is the vacuum-tube voltmeter. Secondly, the thermocouple current is proportional to frequency, so that the arrangement would have a different meter scale for each frequency. Thirdly, the meter scale is not linear,



CYLINDRICAL CAPACITORS. THE SMALLER ONE IS SHOWN DISASSEMBLED.



CYLINDRICAL CAPACITOR

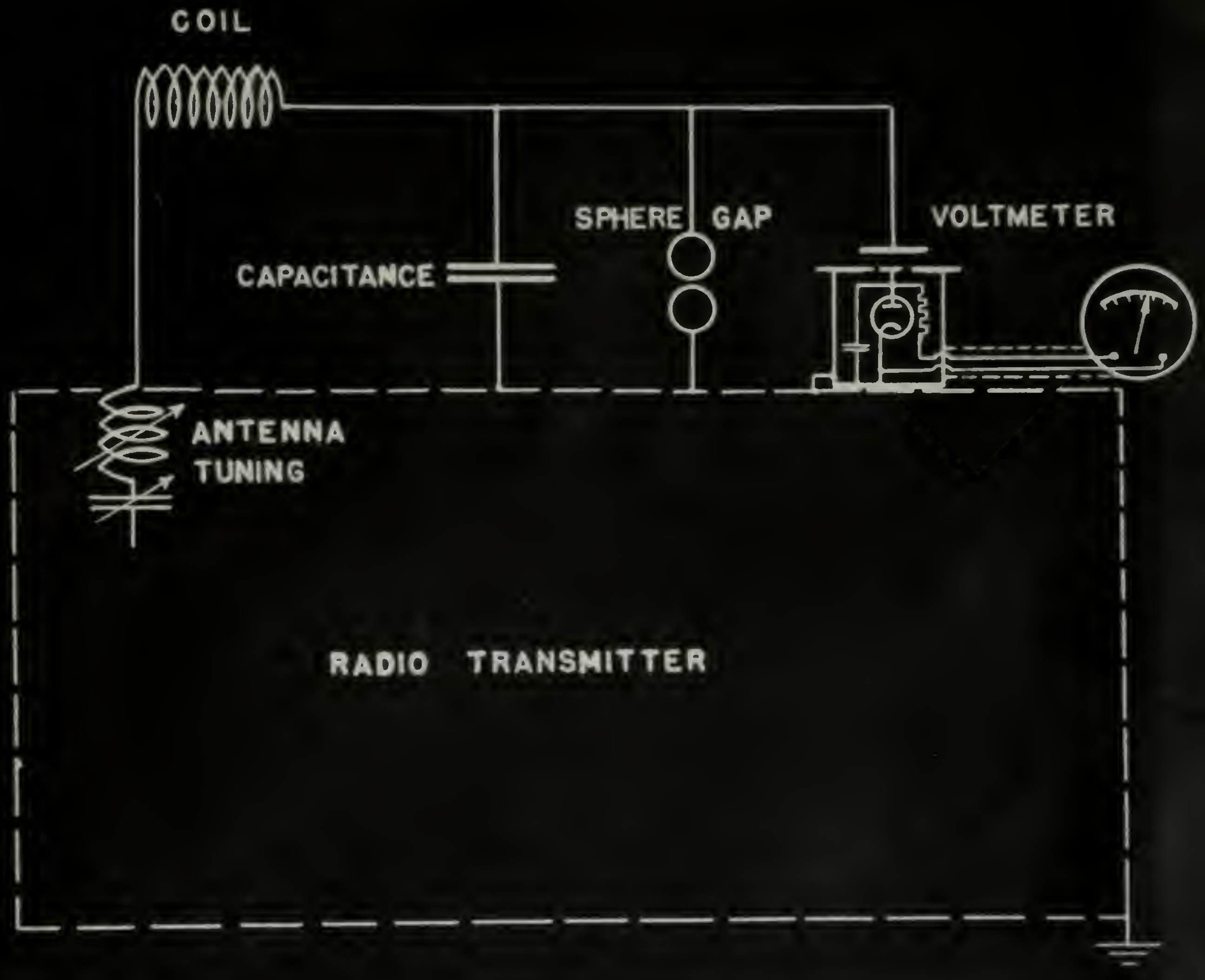
whereas the vacuum-tube voltmeter is. And finally, the thermocouple has a considerable time lag.

<u>Source of Test Voltage</u>:

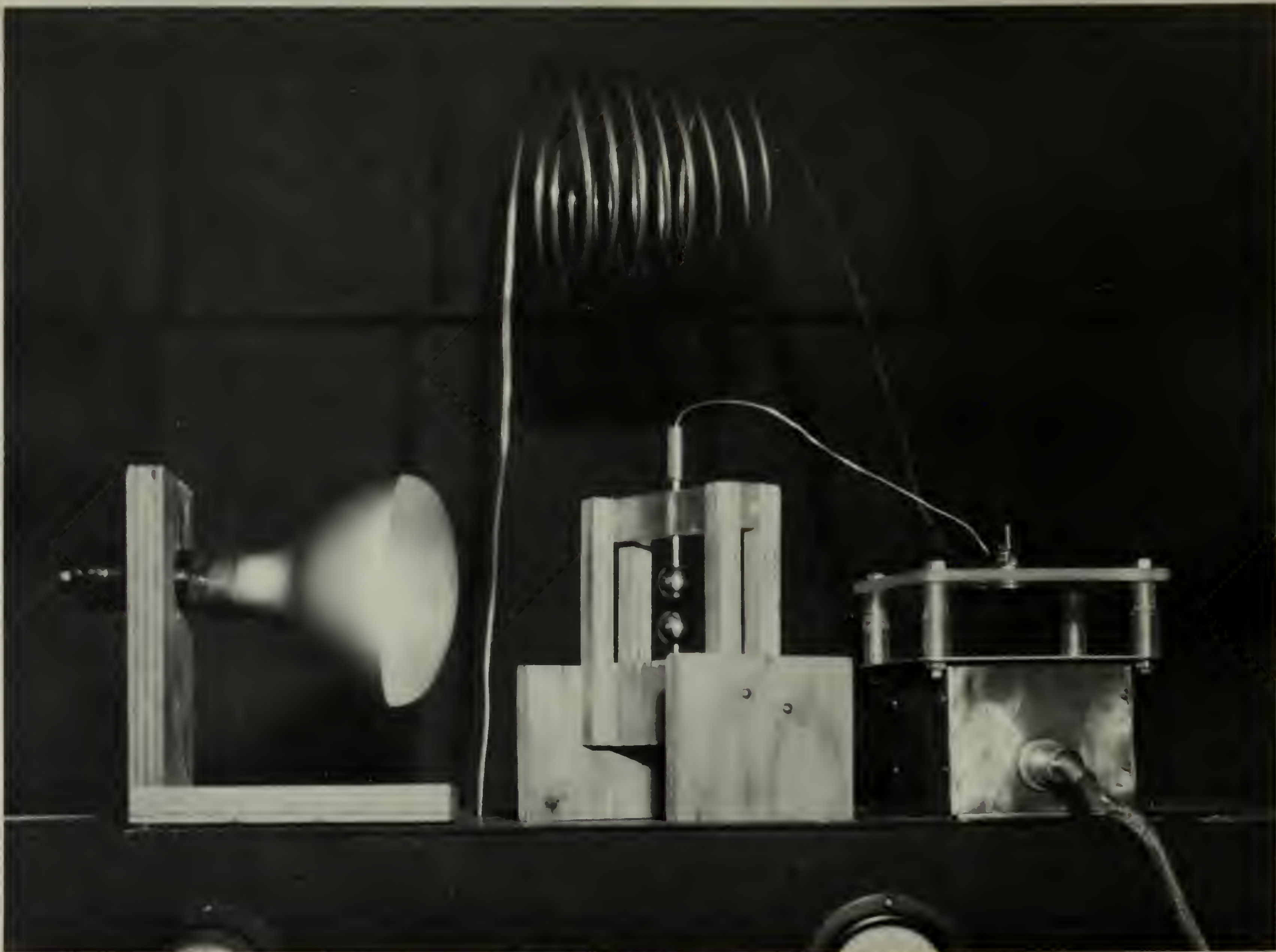
Two Navy-type radio transmitters served as the source of test voltages. One was rated 1000 watts C.W. from 300 kilocycles to 2000 kilocycles, and the other was rated 500 watts C.W. from 2 megacycles to 18 megacycles. These are master-oscillator, power-amplifier type transmitters. The high voltages were obtained by using a series-resonant circuit as load. A schematic diagram appears on page 19, and a photograph of the test set-up on page 20. Suitable coils were constructed, using No. 10 double-cotton-covered wire for the lower frequencies, and 1/4 inch copper tubing for the higher frequencies. The capacitances were simple discs of suitable sizes, set at variable distance above the ground plane. At the higher frequencies, the capacitance of the voltmeter plus the sphere gap or the cylindrical capacitor, was sufficient to achieve resonance.

<u>The Sphere Gaps</u>:

Two sphere gaps were used. The larger had brass spheres 6.25 cm. in diameter, and was made by General Electric Co. The smaller was constructed for this study, using brass spheres 2 cm. in diameter. Specifications of the American Standards Association[1] were followed. In addition, the support for the shank of the upper, ungrounded sphere was



SCHEMATIC DIAGRAM OF TEST SET-UP



THE TESTING SET-UP

made of polystyrene. In all tests the spheres were mounted in a vertical position, with the lower sphere grounded.

A rod gap also was constructed following specifications set forth by the American Standards Association(1). Brass rods, 1/2 inch square and cut off squarely, form the two electrodes. Corners were not rounded off, but burr was removed.

<u>Source of Irradiation:</u>

A simple source of irradiation was chosen. This was a Westinghouse Co. type RS sunlamp, rated 110 volts, 275 watts, which fits into a standard lamp socket. It is a mercury-arc type, with a bulb of special glass which passes considerable ultra-violet light. It was found to be adequate for the purposes of this study.

<u>Testing Procedure:</u>

The following procedure was used to obtain the test data: A selected frequency was set up in the transmitter, and a suitable coil and capacitance arrangement was found which would provide a series-resonant load. The capacitance included the sphere gap and the voltmeter in parallel. Within the transmitter are an antenna loading coil and a coupling condenser which permitted a smooth final adjustment for resonance. The sphere gap was then set at a fixed gap value, determined by means of a feeler gauge, and the plate voltage on the final stage of the transmitter was increased until a preliminary spark-over occurred. Then with this voltage cut off,

the load was de-tuned slightly by means of either the antenna loading coil or the coupling capacitor, so that when plate voltage was re-applied to the output stage, the resultant voltage across the sphere gap was about 90% of spark-over value. This voltage was slowly increased by restoring the resonance through gradual manipulation of the antenna loading coil or coupling capacitor. The transmitter was cut off manually as soon as spark-over occurred, to avoid burning or pitting the spheres. Five such readings were taken. The ultra-violet light was then turned on and five more readings obtained with the spheres irradiated. Finally the sphere-gap setting was rechecked, before resetting to a new gap value.

Atmospheric pressure was read from a mercury-column barometer. Temperature and humidity were recorded from a wet and dry bulb thermometer.

Cleaning the spheres with crocus cloth, carbon tetrachloride, and soft cloth seemed to produce no effect on the results. Consequently, a great many spark-overs were recorded before stopping to clean the spheres.

EXPERIMENTAL RESULTS

The results of this study are presented in the form of curves, on pages 28 to 40. The original data are tabulated in Appendix B. For purposes of comparison, the spark-over

values for irradiated 2-cm spheres at 50 cycles[17], together with the values found for irradiated spheres at the frequencies used in this investigation, are plotted on page 33. Wherever the scattering of the data is significant, the individual observations are plotted. Otherwise each point represents the average of five or more observations.

DISCUSSION OF RESULTS

The most noteworthy feature of the results is their consistency, particularly over such a wide range of frequencies. The consistency of individual observations, for a given gap setting and frequency, is also remarkable when the gap is irradiated. When the spheres are not irradiated, this consistency is not as good, and the readings are generally somewhat higher. This is in agreement with the results of other investigators. [4,7,13,14,15,16]

For very small gaps, if the frequency was not too high, the spark-over voltage seemed to coincide with that for power frequency. Then as the gap length was increased, there was a semi-abrupt transition to the lower spark-over values that are characteristic of the high frequencies. This effect is most clearly shown in the curves of spark-over voltages vs. frequency for fixed values of gap setting, page 38.

A possible theory to account for this is presented. A sinusoidal voltage having crest value slightly less than spark-over value, during its peak may form incipient breakdown streamers of ionized air part way across the gap.

During the remainder of the half-cycle, these ions will be attracted toward the sphere surfaces, and if the cycle is not too brief, or the distance to be travelled not too long, effective de-ionization of the gap will take place before the next voltage peak occurs.* At power frequency, this takes place for any gap of reasonable length. And if this theory is correct, the experimental results of this study indicate that this de-ionization takes place for example, at 300 kilocycles for a gap length of 1 millimeter, but does not take place if the gap is 2 millimeters. From this, a rough calculation gives a figure for ion mobility of about 3 cm/sec/volt/cm. (See Appendix A). This is in good agreement with the value 3 - 4 cm/sec/volt/cm derived recently by another investigator[19] from probe measurements of 60-cycle corona.

Another feature of the curves of spark-over voltage vs. frequency, for various fixed gap lengths, page 38, is the appearance of definite minima. These minima are functions of gap length and frequency, as is most clearly shown by the curve on page 39, where the reciprocal of the frequency at which the minimum occurs for a fixed gap length, is plotted against gap length. The nearly linear form of this curve suggests that the product gf_m is relatively constant, where g is gap length and f_m is the frequency at which the minimum occurs. The product gf_m, over the range of gaps from 0.77 millimeters to 6 millimeters, is found to be $(4 \pm 0.5) \times 10^5$,

- -

*This theory is essentially the same as that proposed by Pim[20], who studied gaps of less than 1 millimeter, at frequencies from 100 to 300 megacycles.

where f_m is in cycles per second, and g is in centimeters.

To account for these minima, the possibility of ionic oscillations was considered. Such oscillations, at frequencies of the same order of magnitude as these minima, (about 1 megacycle) have been reported in the study of the plasma of low-pressure gaseous discharges[26]. Their velocity of propagation v can be calculated theoretically from $v = \left(\frac{kT}{M}\right)^{1/2}$, where k is the Boltzmann constant, T is the electron temperature, and M is the mass of an ion. (For nitrogen, $M = 23.27 \times 10^{-24}$ grams). Assuming T to be about 30,000 degrees absolute, gives a velocity of propagation $v = 4.2 \times 10^5$ centimeters per second. Now on page 38, the curve for a 6-millimeter gap shows a minimum at about 550 kilocycles (point A). Assuming an ionic oscillation to exist, and its wavelength to be twice the gap length, a velocity of propagation of 6.6×10^5 centimeters per second is calculated. This is in fair agreement with that calculated from the theory.

A resonance between the frequency of applied field and ionic oscillations could serve to lower the breakdown voltage of the gap, because at resonance the ionic oscillations would be enhanced, and additional energy would be supplied to the gap by the applied voltage. An increase of ionization, and lowered break-down strength would logically result.

In the curves, page 38, there is also some evidence of a second set of minima to be expected at much higher frequencies than those used in this investigation. These could be associated with a resonance effect involving electronic

oscillations. The ratio of the mass of a nitrogen ion to that of an electron is about 26000 to 1. Assuming the resonant frequency to vary inversely as the square root of the mass, a second minimum might therefore be expected at a frequency 160 times that which has been ascribed to ionic oscillations. The conjectured appearance of such a minimum at about 10^8 cycles per second (point B), has been sketched in a dotted extrapolation of the curve on page 38, for the case of a gap length of 6 millimeters. Electronic oscillations having frequencies of this order of magnitude have been found in studies of the plasma of gaseous discharges(26).

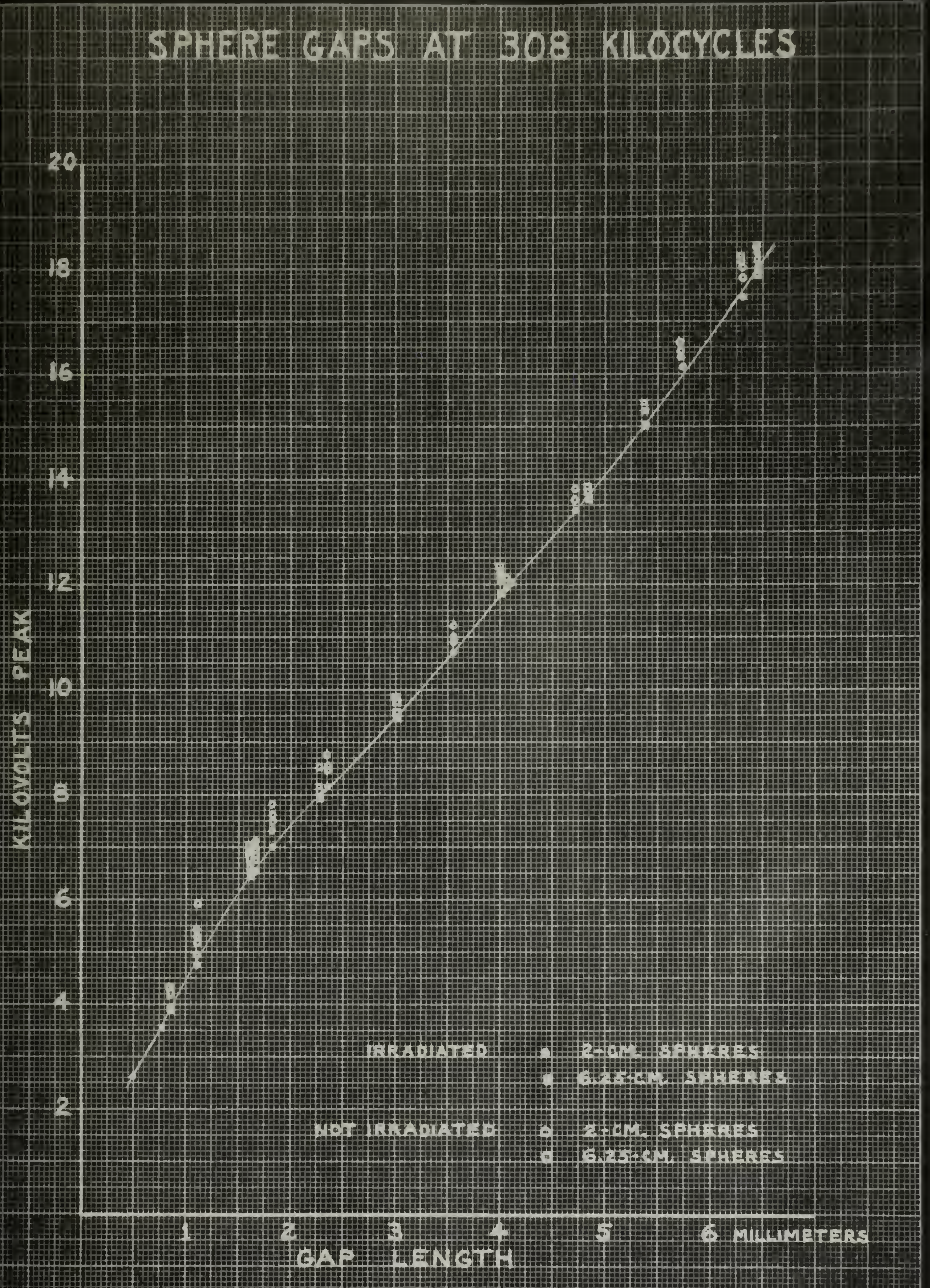
The sphere-gap results are in general agreement with previous studies, particularly those of Ekstrand(6), who made tests with 2-cm. irradiated spheres at 700 kilocycles and 1800 kilocycles. Seward(4) and Alford and Pickles(5) report values about 15% higher, and Reukema(5) values about 5% lower than those of this investigation, for corresponding frequencies. These differences may be due to the lack of irradiation, and to the use of a different intensity of irradiation, respectively, because apparently spark-over value does decrease somewhat with increased intensity of irradiation. (13,14,15,16) During this investigation, the ultra-violet light was maintained at a distance of 10 cm. from the gap, for the sake of uniformity. However, moving the lamp closer seemed to produce no measurable difference in the spark-over values.

The rod gap was investigated, because it appears in the American Standards Association publication(1). Its use at these high frequencies does not seem to offer a great promise. For very small gap settings the results tend to be erratic, while for gaps much over 2 cm., corresponding to about 14 kilovolts peak, there was an unpredictable tendency for a flamelike discharge to strike from any one of the sharp corners of the upper electrode. This discharge would not strike to the lower, grounded electrode, but would extend out into space, more or less like corona. About the only feature in favor of the rod gap is its ease of construction.

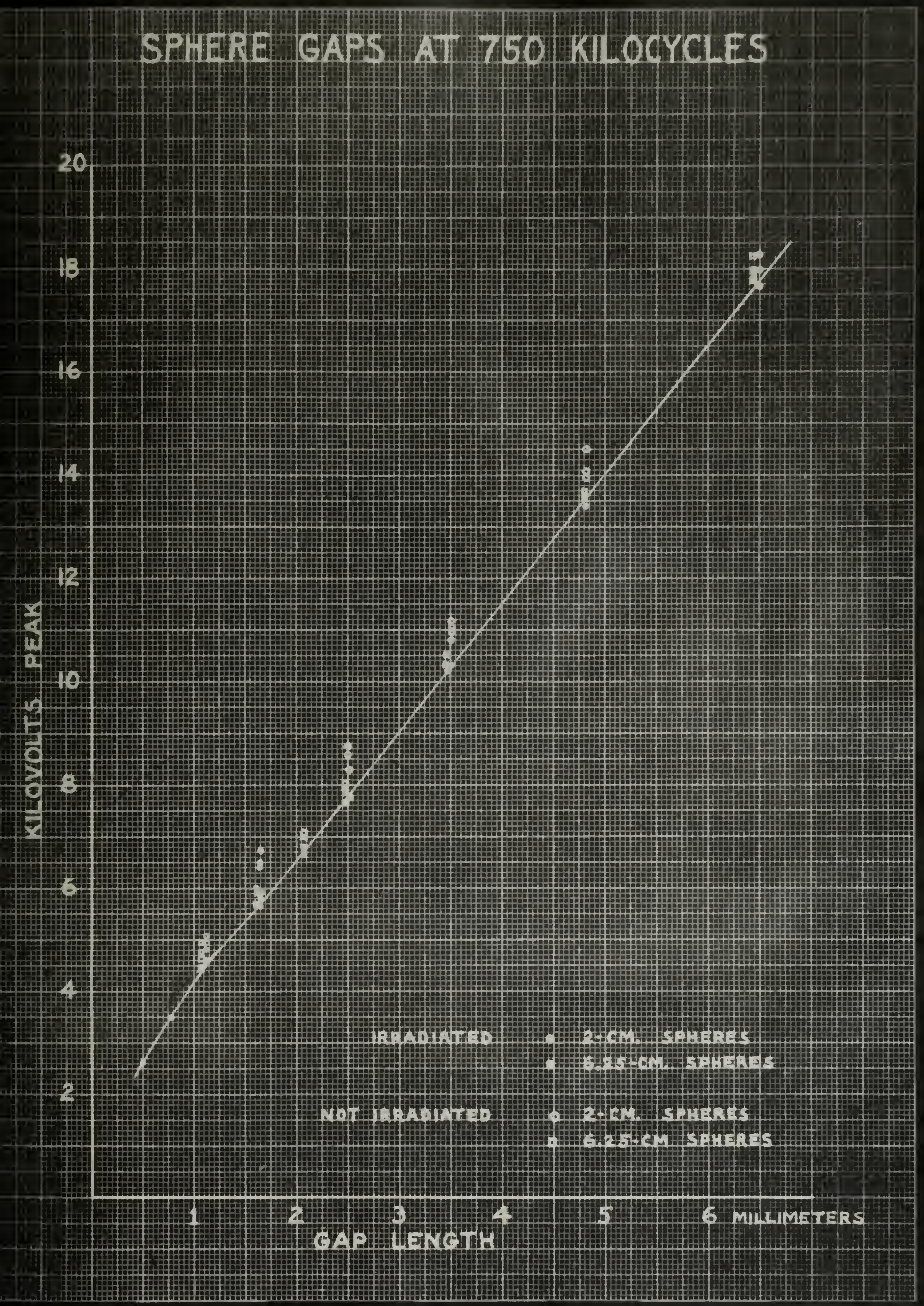
On page 40 there is presented in graphical form a survey of published test results on the dielectric strength of air, covering a broad range of frequencies. The results of this report are included, for comparison. The various investigations were conducted under widely different conditions, so that not all are subject to direct comparison. In compiling this survey, the values corresponding to irradiated spheres with a gap spacing of 0.5 cm. were chosen wherever possible.* This survey indicates that over a wide spectrum of frequencies, the dielectric strength of air does not vary a great deal.

- -

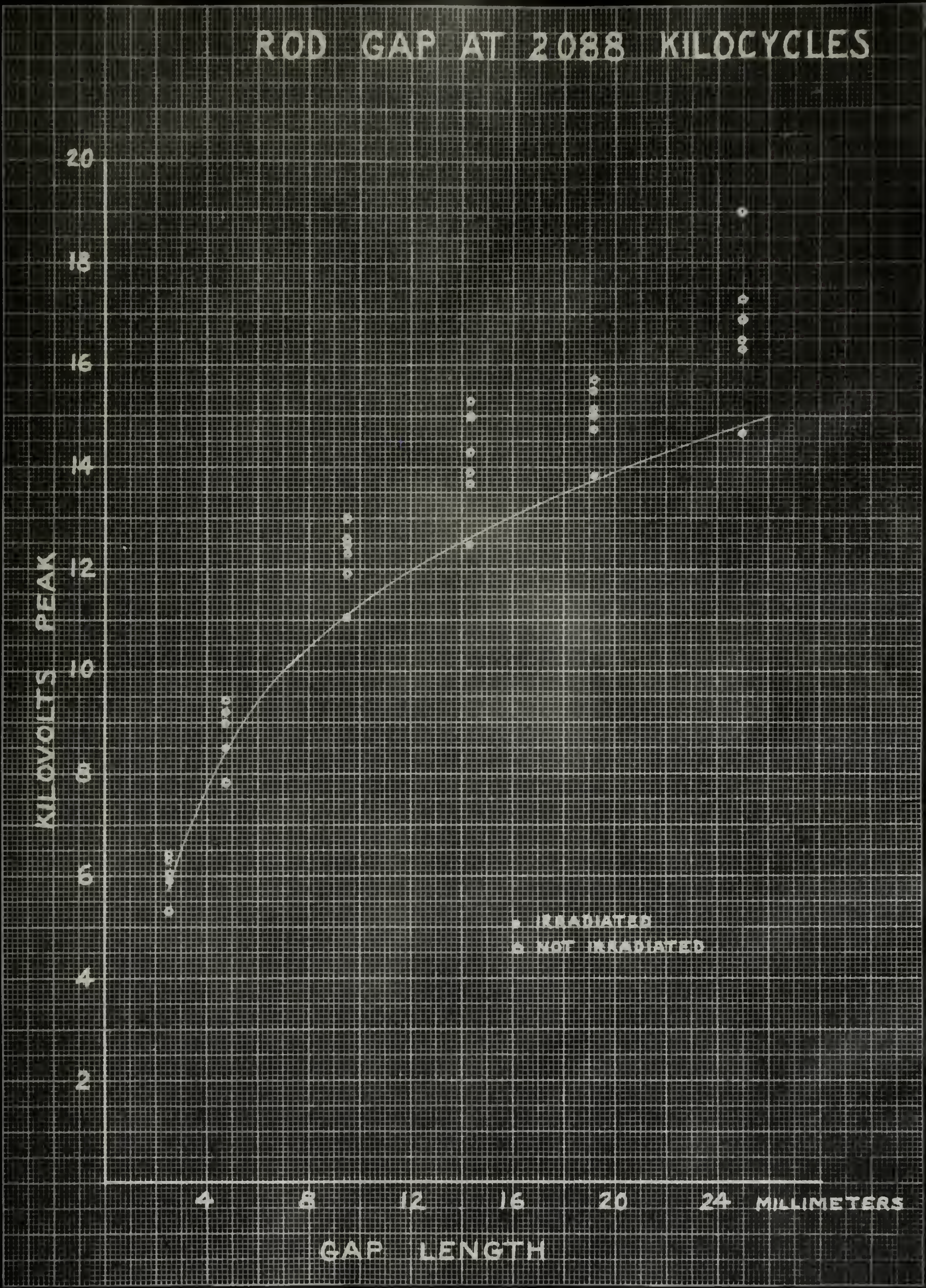
* In computing the dielectric strength of air at high frequencies, from the spark-over voltages of the various sphere gaps, the correction factor set forth by Peek, (2, page 28) was not used, because the results of this report, and a study of the available published data, indicate that this correction factor does not apply at high frequencies, for the sphere sizes and gap lengths considered.



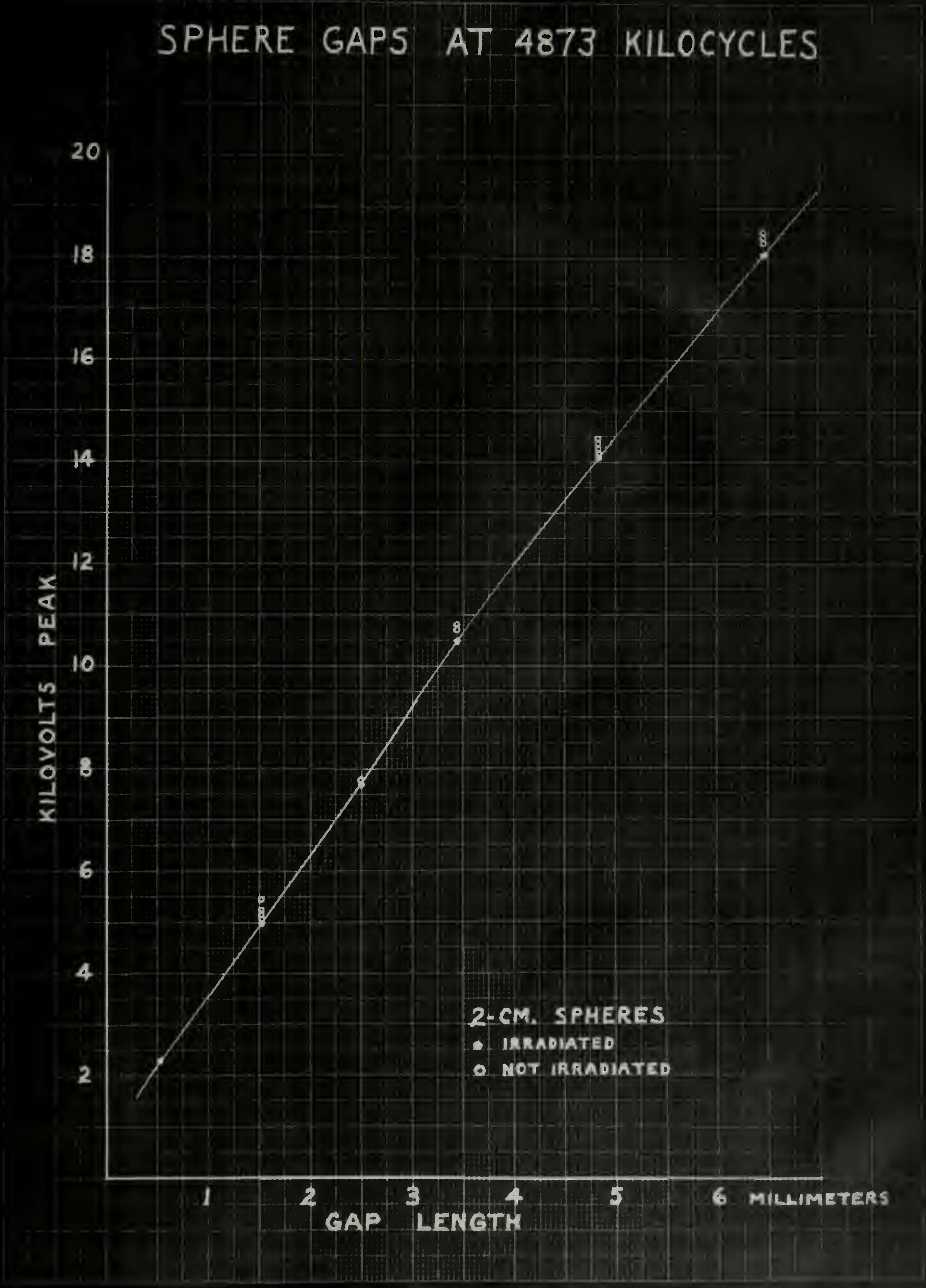
SPHERE GAPS AT 308 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6 MILLIMETERS
GAP LENGTH
IRRADIATED
2-CM. SPHERES
6.25-CM. SPHERES
NOT IRRADIATED
2-CM. SPHERES
6.25-CM. SPHERES



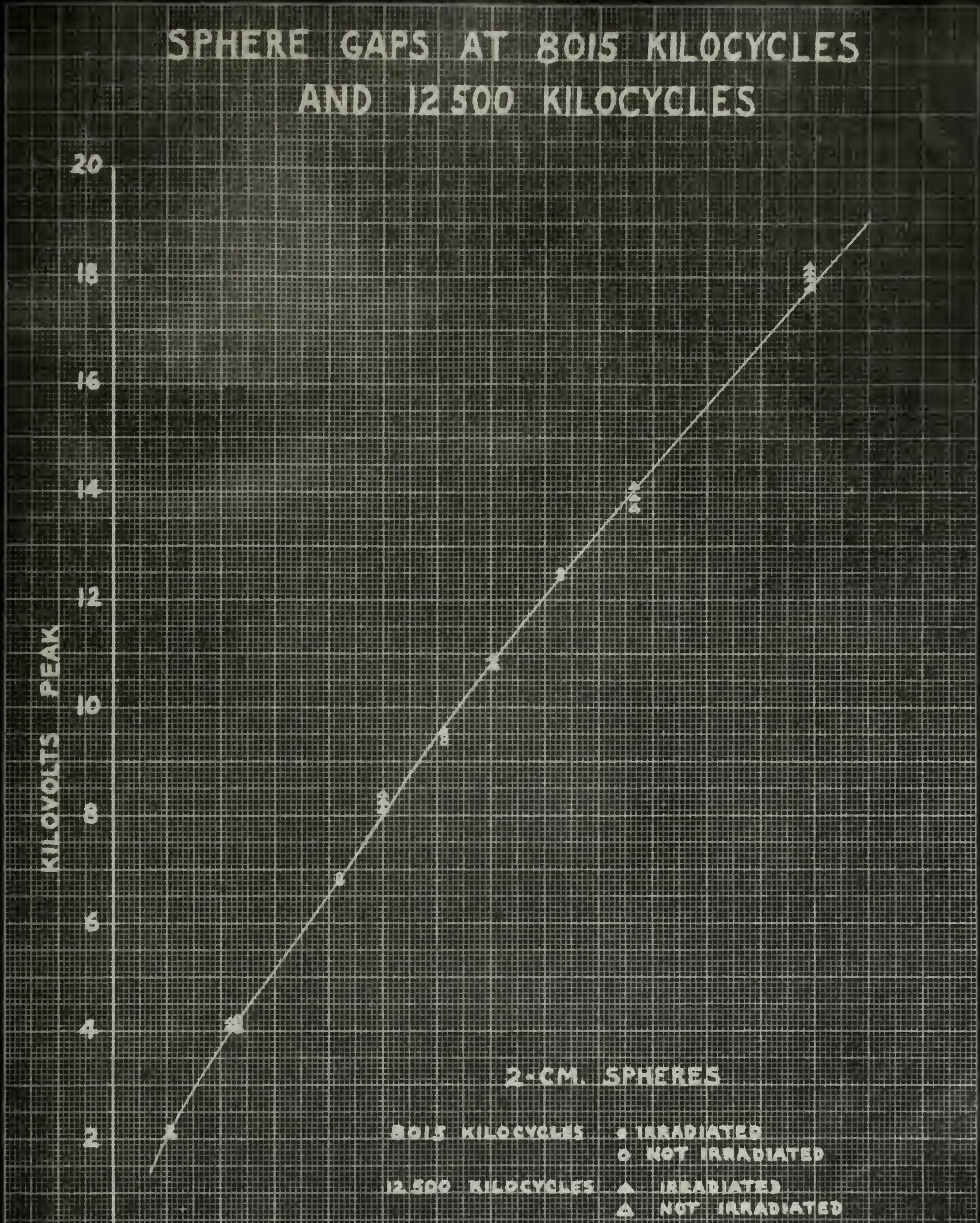
SPHERE GAPS AT 750 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
IRRADIATED
2-CM. SPHERES
6.25-CM. SPHERES
NOT IRRADIATED
2-CM. SPHERES
6.25-CM SPHERES
1
2
3
4
5
6 MILLIMETERS
GAP LENGTH



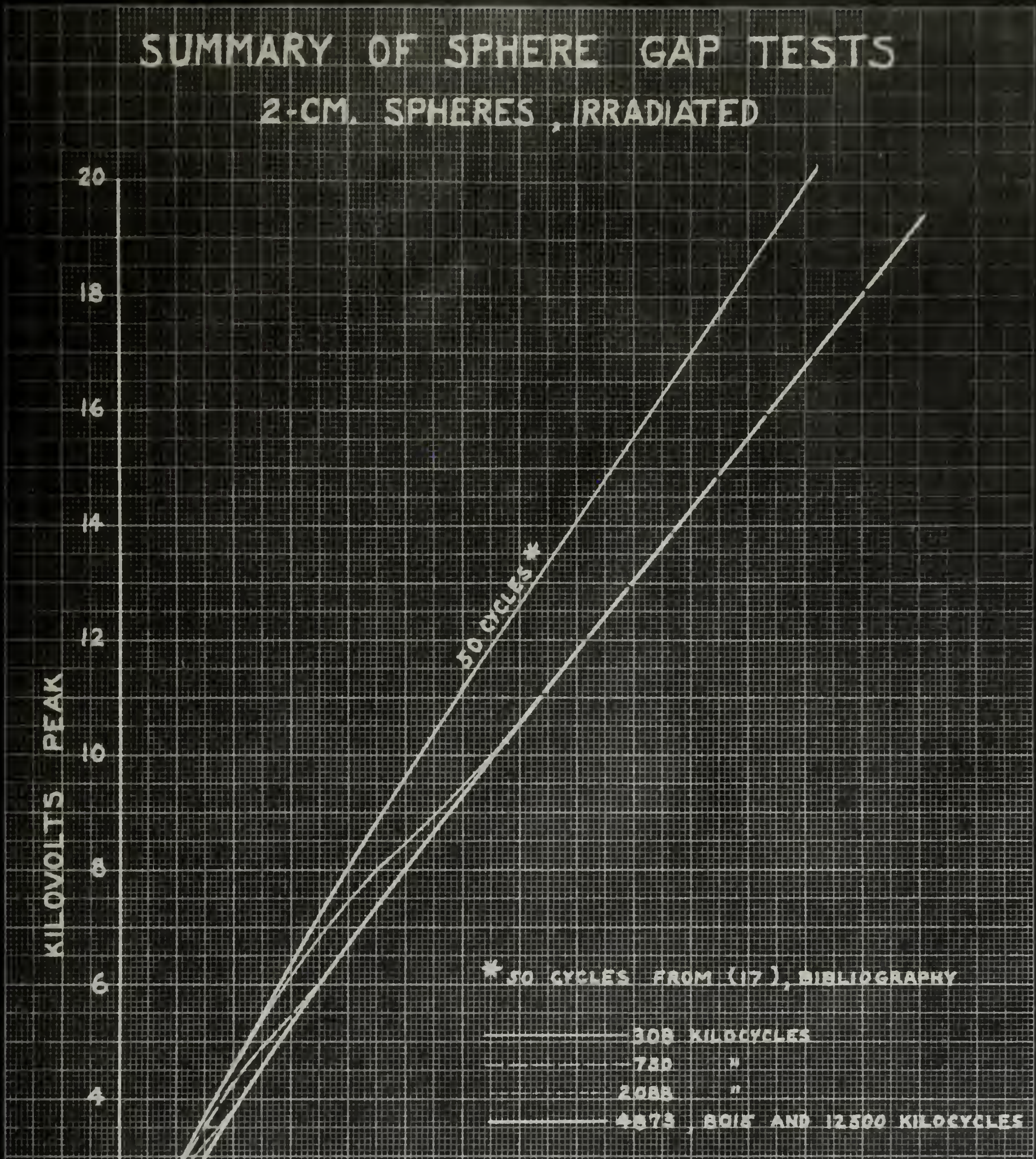
ROD GAP AT 2088 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
4
8
12
16
20
24
MILLIMETERS
GAP LENGTH
IRRADIATED
NOT IRRADIATED



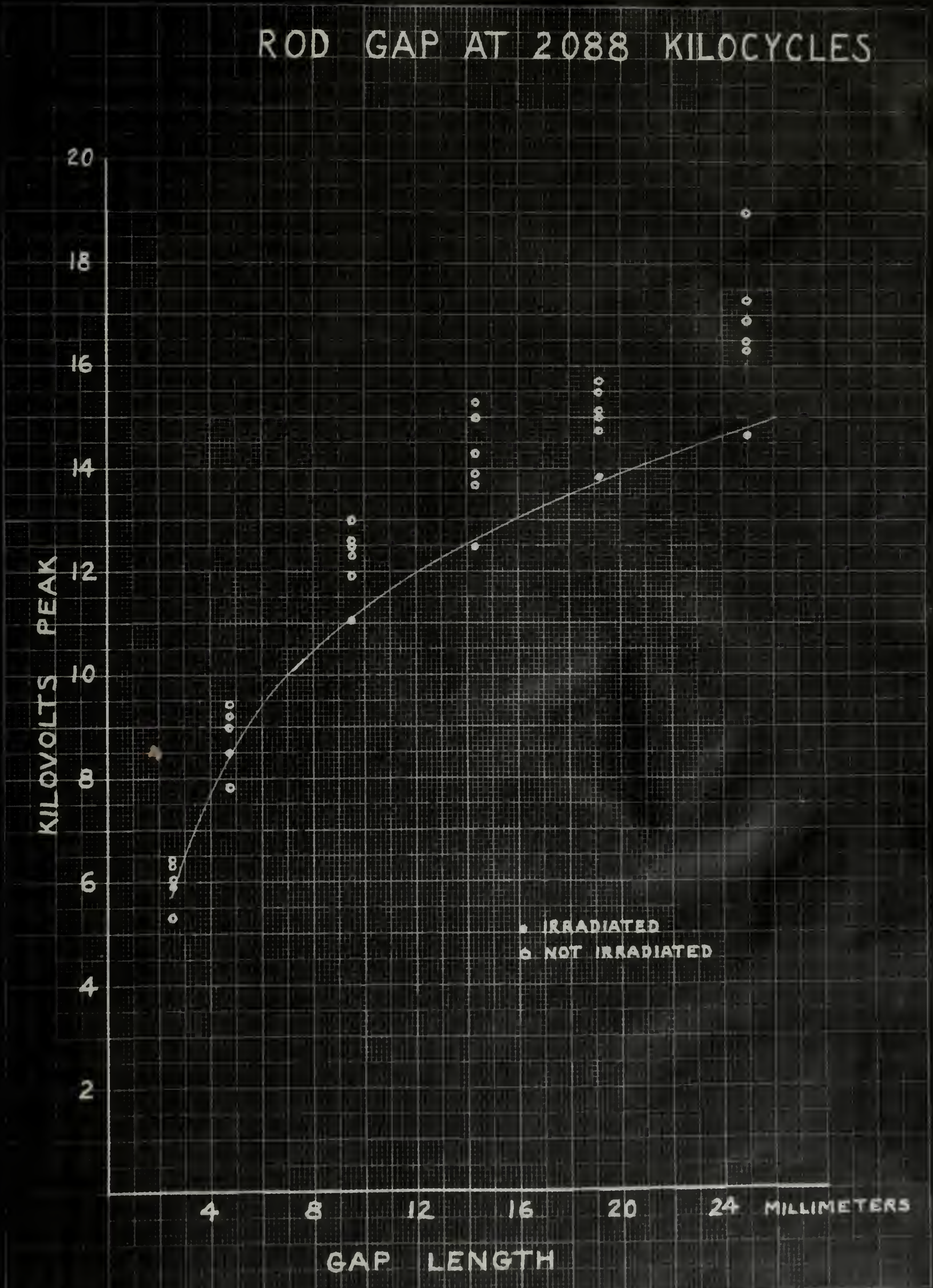
SPHERE GAPS AT 4873 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
1
2
3
4
5
6
MILLIMETERS
GAP LENGTH
2-CM. SPHERES
IRRADIATED
NOT IRRADIATED



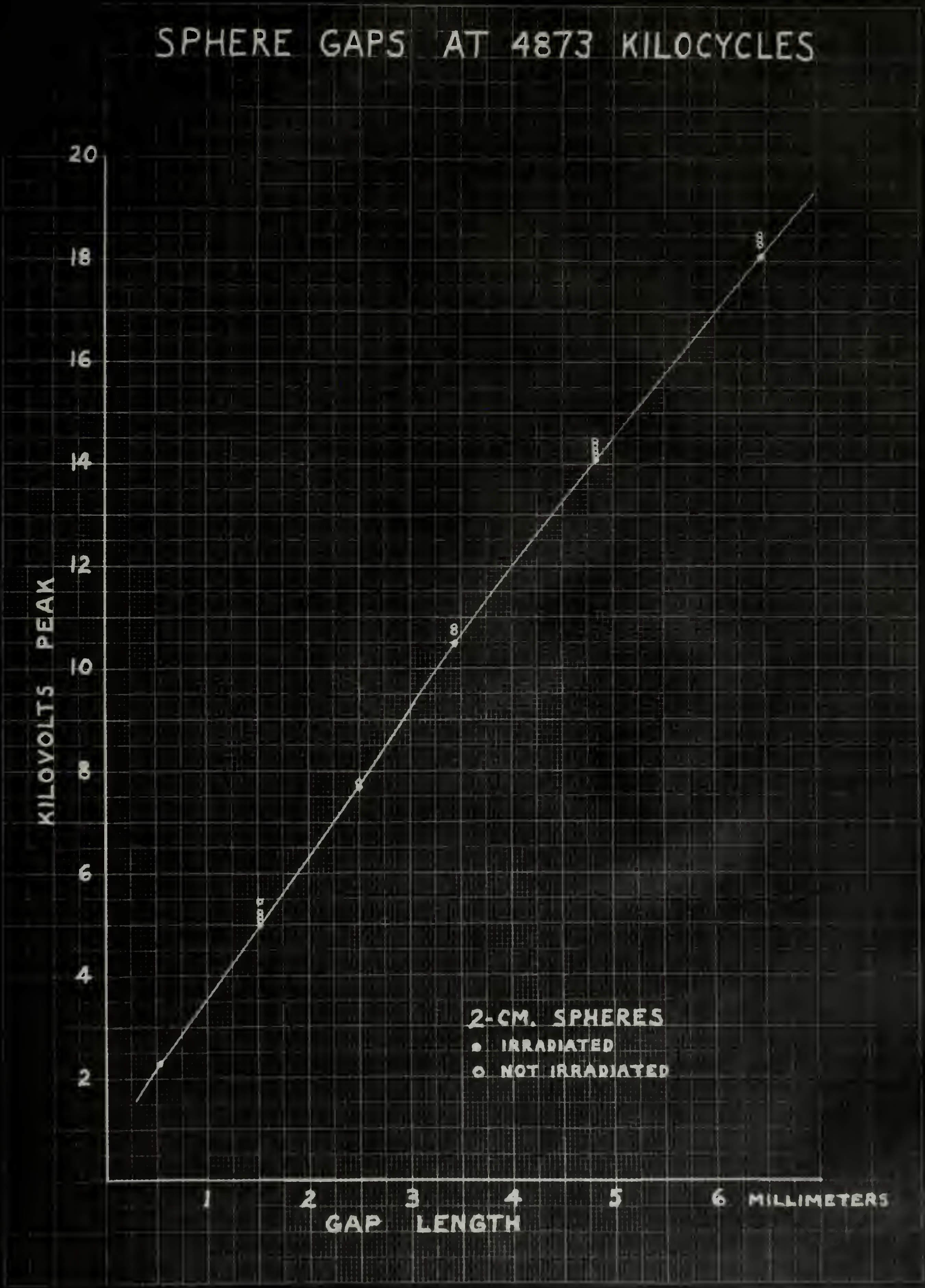
SPHERE GAPS AT 8015 KILOCYCLES
AND 12 500 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
2-CM. SPHERES
8015 KILOCYCLES • IRRADIATED
o NOT IRRADIATED
12 500 KILOCYCLES ▲ IRRADIATED
△ NOT IRRADIATED
1
2
3
4
5
6
MILLIMETERS
GAP LENGTH

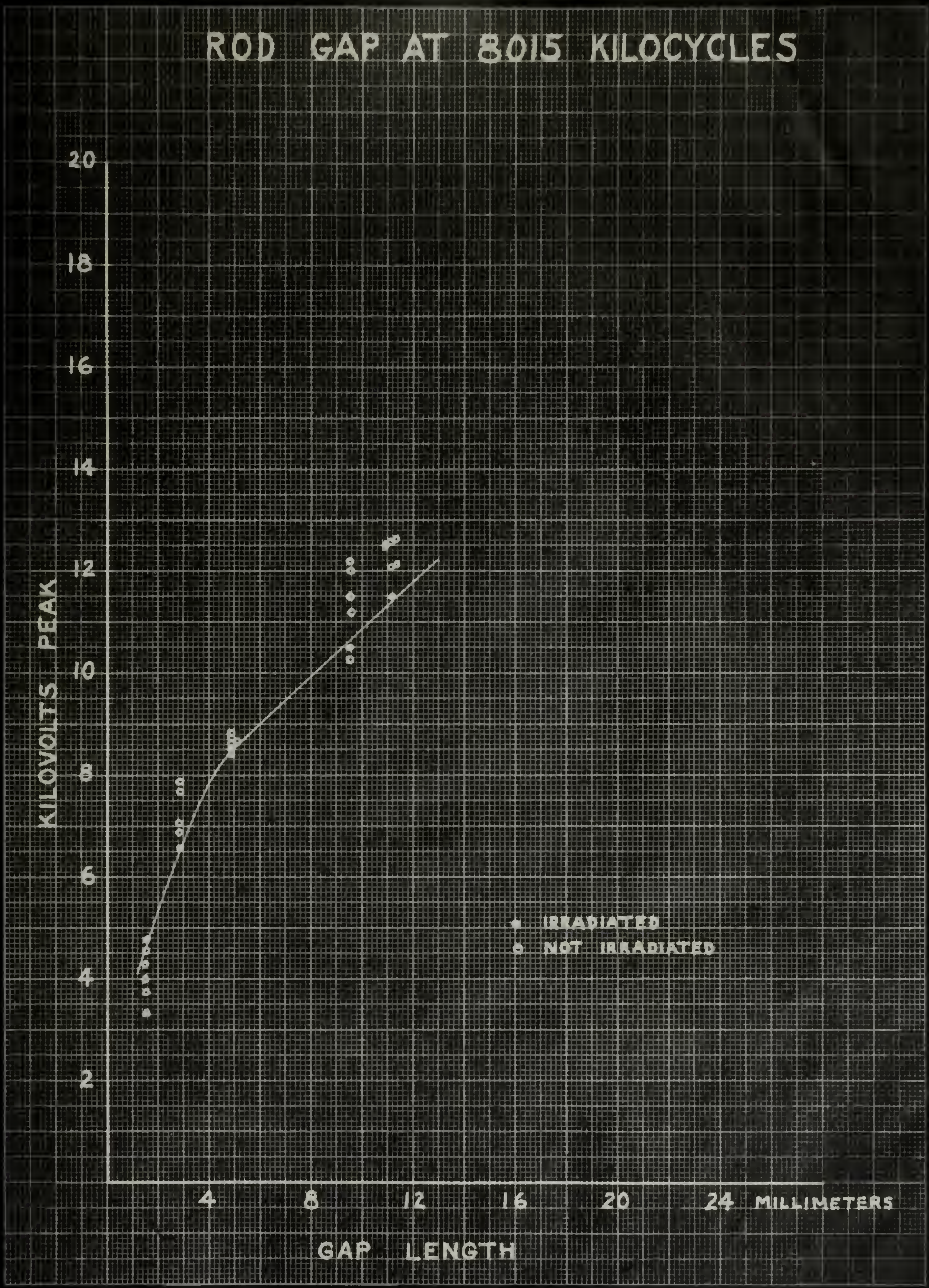


SUMMARY OF SPHERE GAP TESTS
2-CM. SPHERES, IRRADIATED
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
50 CYCLES
* 50 CYCLES FROM (17), BIBLIOGRAPHY
308 KILOCYCLES
730 "
2088 "
4873, 8015 AND 12,500 KILOCYCLES
AVERAGE, 308-12500 KILOCYCLES
(DEVIATIONS LESS THAN 2%)
1
2
3
4
5
6
MILLIMETERS
GAP LENGTH

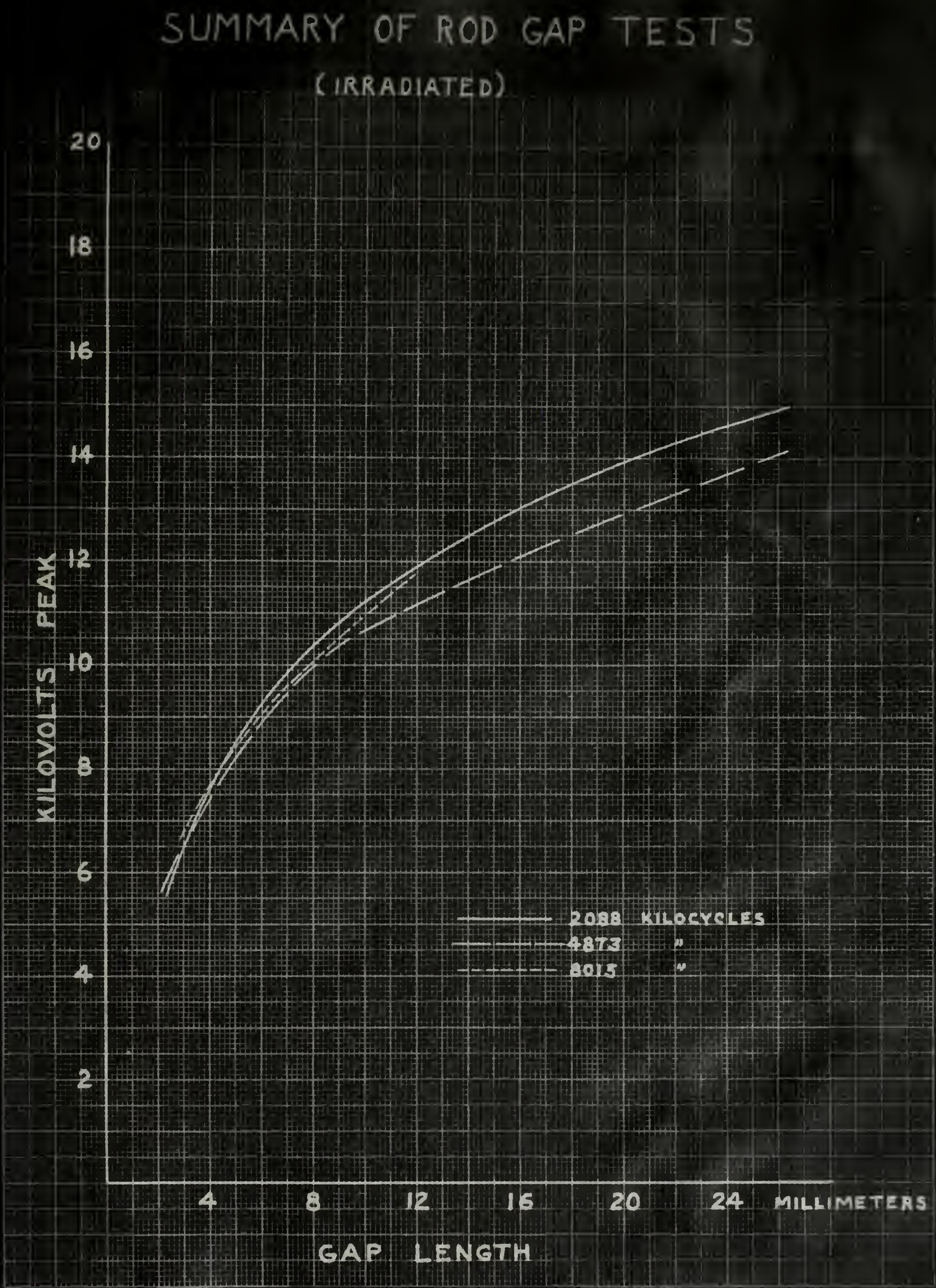


ROD GAP AT 2088 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
4
8
12
16
20
24
MILLIMETERS
GAP LENGTH
IRRADIATED
NOT IRRADIATED

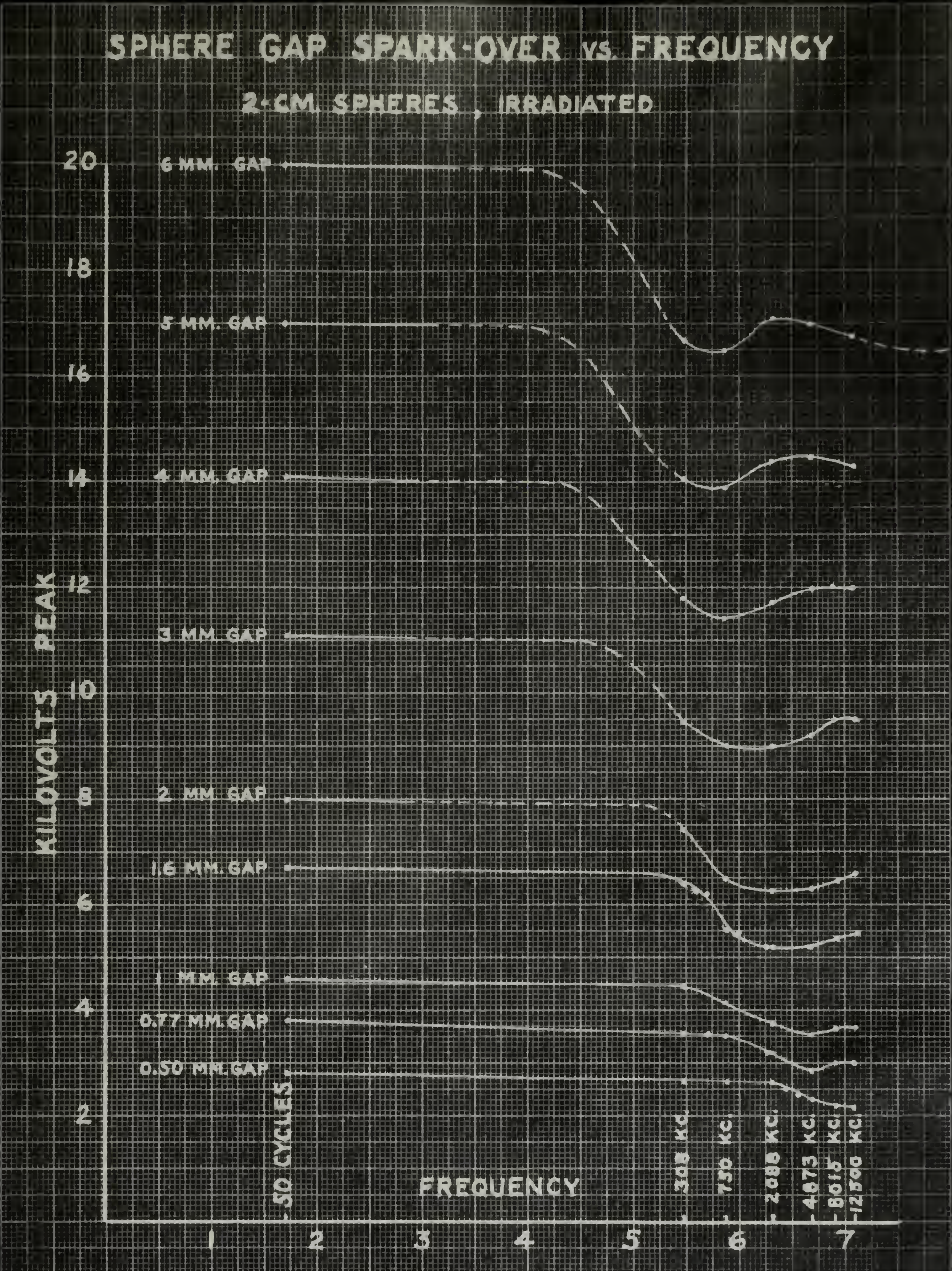

SPHERE GAPS AT 4873 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
1
2
3
4
5
6
MILLIMETERS
GAP LENGTH
2-CM. SPHERES
IRRADIATED
NOT IRRADIATED

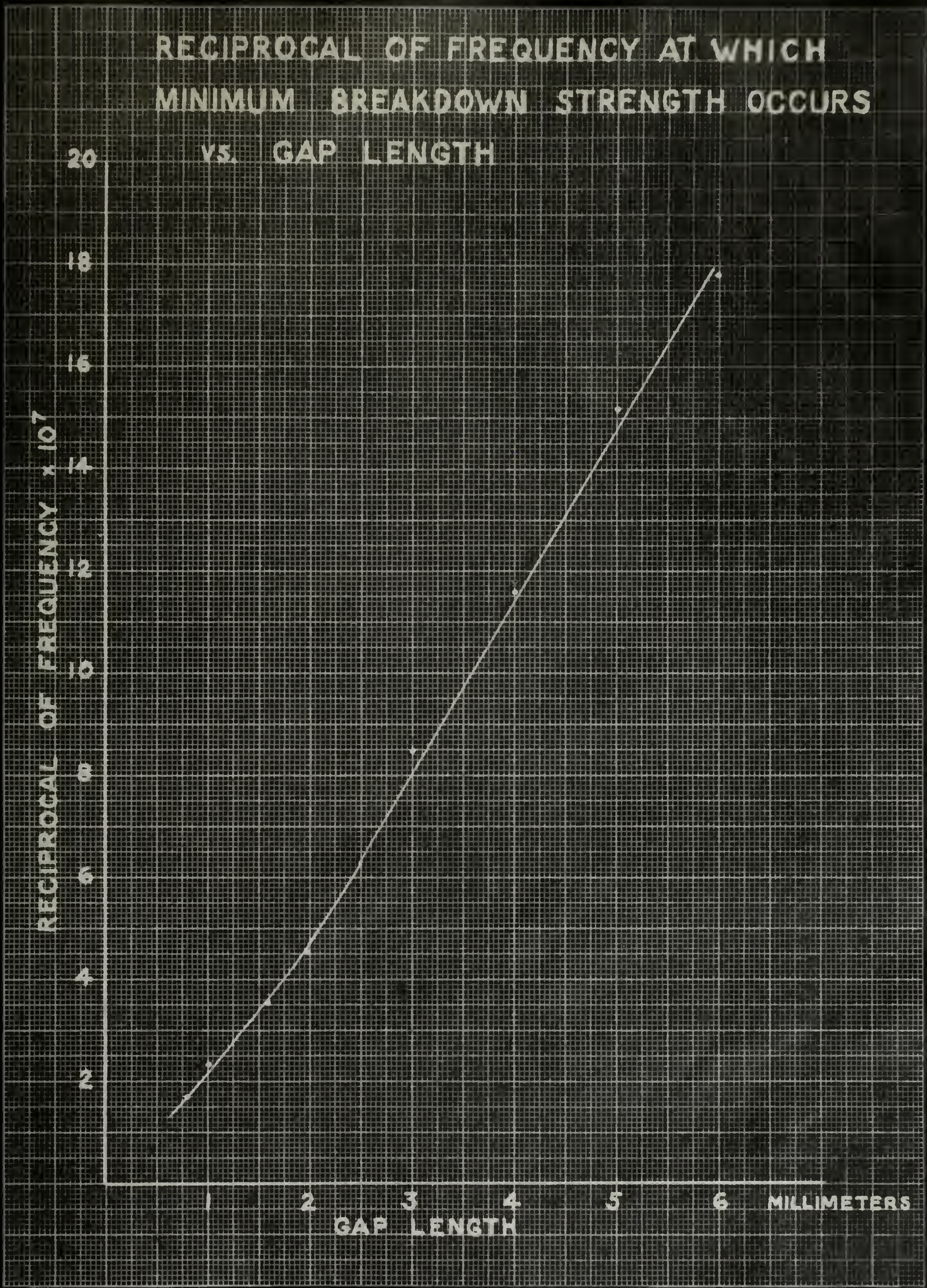


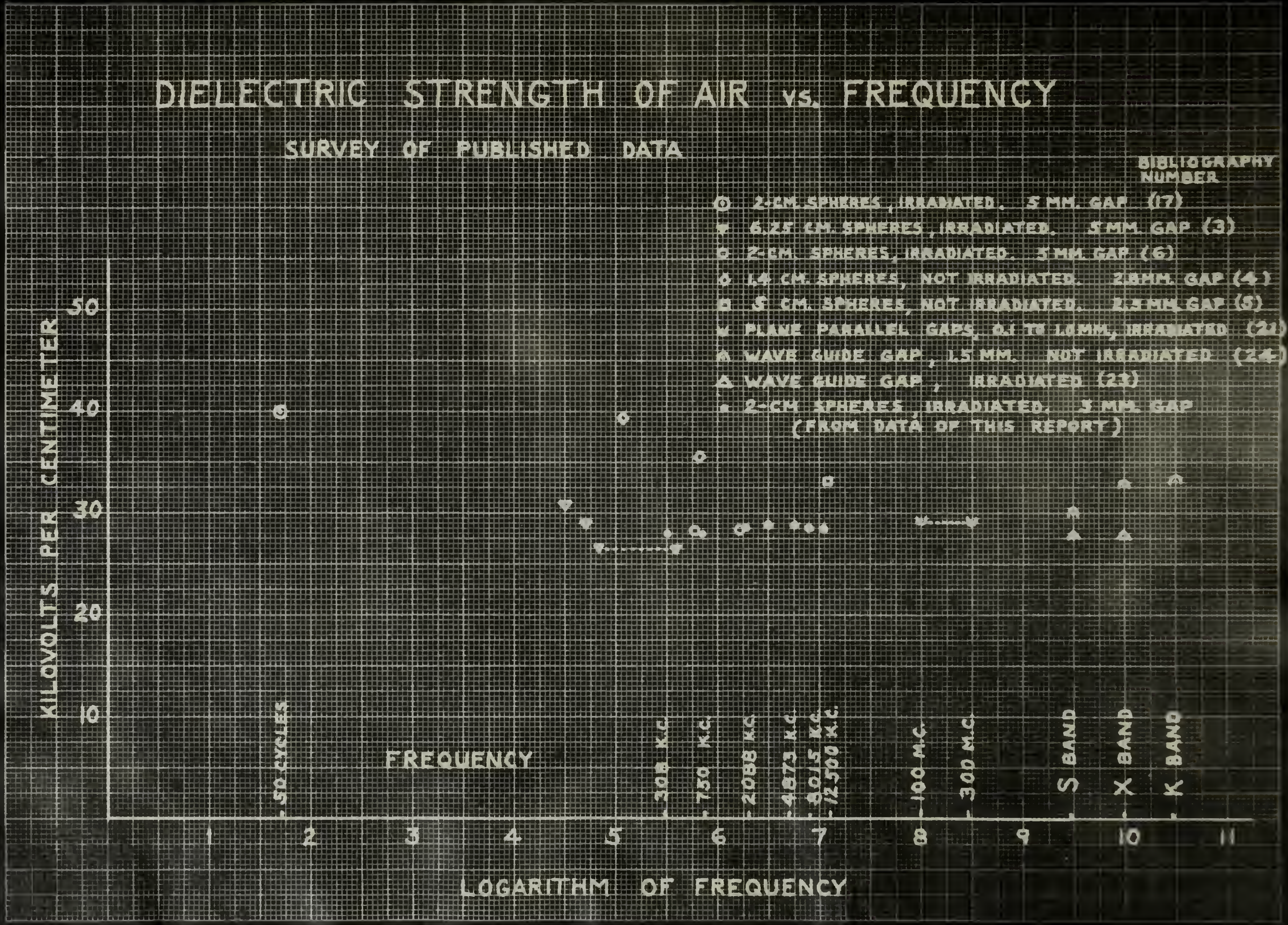
ROD GAP AT 8015 KILOCYCLES
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
4
8
12
16
20
24
MILLIMETERS
GAP LENGTH
IRRADIATED
NOT IRRADIATED



SUMMARY OF ROD GAP TESTS
(IRRADIATED)
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
2088 KILOCYCLES
4873 "
8015 "
4
8
12
16
20
24
MILLIMETERS
GAP LENGTH


SPHERE GAP SPARK-OVER vs FREQUENCY
2-CM. SPHERES, IRRADIATED
KILOVOLTS PEAK
20
18
16
14
12
10
8
6
4
2
6 MM. GAP
5 MM. GAP
4 MM. GAP
3 MM. GAP
2 MM. GAP
1.6 MM. GAP
1 MM. GAP
0.77 MM. GAP
0.50 MM. GAP
50 CYCLES
FREQUENCY
303 KC.
750 KC.
2,088 KC.
4,673 KC.
8015 KC.
12,500 KC.
1
2
3
4
5
6
7
LOGARITHM OF FREQUENCY


RECIPROCAL OF FREQUENCY AT WHICH
MINIMUM BREAKDOWN STRENGTH OCCURS
VS. GAP LENGTH
RECIPROCAL OF FREQUENCY × 10⁷
20
18
16
14
12
10
8
6
4
2
1
2
3
4
5
6
MILLIMETERS
GAP LENGTH


DIELECTRIC STRENGTH OF AIR vs. FREQUENCY
SURVEY OF PUBLISHED DATA
BIBLIOGRAPHY NUMBER
2-CM. SPHERES, IRRADIATED. 5 MM. GAP (17)
6.25 CM. SPHERES, IRRADIATED. 5 MM. GAP (3)
2-CM. SPHERES, IRRADIATED. 5 MM. GAP (6)
1.4 CM. SPHERES, NOT IRRADIATED. 2.8MM. GAP (4)
5 CM. SPHERES, NOT IRRADIATED. 2.5 MM. GAP (5)
PLANE PARALLEL GAPS, 0.1 TO 1.0 MM., IRRADIATED (21)
WAVE GUIDE GAP, 1.5 MM. NOT IRRADIATED (24)
WAVE GUIDE GAP, IRRADIATED (23)
2-CM. SPHERES, IRRADIATED. 5 MM. GAP
(FROM DATA OF THIS REPORT)
KILOVOLTS PER CENTIMETER
50
40
30
20
10
FREQUENCY
50 CYCLES
308 K.C.
750 K.C.
2088 K.C.
4873 K.C.
8015 K.C.
12,500 K.C.
100 M.C.
300 M.C.
S BAND
X BAND
K BAND
1
2
3
4
5
6
7
8
9
10
11
LOGARITHM OF FREQUENCY

CONCLUSIONS

The use of sphere gaps for the measurement of moderately high voltages at high frequencies, has been investigated and found to be quite practical in the ranges of frequency and voltage considered. In fact, a small sphere-gap, with controlled irradiation, is shown to be an accurate and extremely simple method for measuring these voltages. Data are presented for frequencies from 300 kilocycles to 12.5 megacycles, and for voltages up to about 20 kilovolts peak. The results overlap and are in general agreement with data which have been published in the lower part of this frequency range, - up to 1.8 megacycles -, and considerably extend this range into frequencies regarding which no comparable data are available.

In the course of the investigation, it was noted that the decrease of breakdown voltage with frequency was not a smooth function, but was more in the nature of a transition from one value for lower frequencies to a reduced value for higher frequencies. A theoretical consideration of this effect appears in the discussion of results, and an approximate value of ion mobility is deduced, based on the theory proposed and the observed data. The value of ion mobility is in good agreement with other published figures.

Definite minima were observed when spark-over voltages for fixed gap lengths were plotted against frequency. These are ascribed to ionic oscillation, and calculations are set

forth which serve to substantiate this theory. It is noted that the frequencies of these minima lie in the same range as published values for ionic resonance frequencies detected in the plasma of gaseous discharges.

The probability of a second set of minima, at frequencies much higher than those used in this study, is noted from the plotted results. It is suggested that these higher-frequency minima may be related to electronic oscillations.

APPENDIX A

1. Calculation of Optimum Breakdown Frequency for Air at Atmospheric Pressure.

The force on an electron in an alternating field is $F = e E \sin \omega t$,

where F is the force in dynes;

e is the electronic charge, in e.s.u.;

E is the peak value of the field strength in statvolts per centimeter;

ω is the frequency in radians per second and

t is time in seconds.

The electron acceleration will be $a = \frac{F}{m}$, where m is its mass in grams.

Taking E to be 90 statvolts per centimeter, which is slightly lower than the breakdown value for atmospheric air, and substituting well known values for e and m, gives

$a = 4.77 \times 10^{19} \sin \omega t$ (cm/sec^2.)

Now velocity $v = \int a dt = - \frac{4.77 \times 10^{19}}{\omega} \cos\omega t$ (cm/sec)

and displacement $d = \int v\, dt = \frac{-4.77 \times 10^{19}}{\omega^2} \sin \omega t$ (cm.)

maximum displacement occurs for $\sin\omega t = -1$, so the maximum displacement is $\frac{4.77 \times 10^{19}}{\omega^2}$ (cm).

Now the mean-free path of an electron in atmospheric air is approximately 5×10^{-5} centimeters. Equating this to the displacement calculated above gives $\frac{4.77 \times 10^{19}}{\omega^2} = 5 \times 10^{-5}$ (cm)

Hence $\omega^2 = 10^{24}$ (approximately)

Or $\omega = 10^{12}$ radians per second.

or frequency $= \dfrac{\omega}{2\pi} = 10^{11}$ cycles per second (approximately)

This represents the order of magnitude of the frequency for optimum breakdown; or in other words, the frequency at which the dielectric strength of atmospheric air would be a minimum.

2. Calculation of Ion Mobility.

The drift velocity v of an ion in a gas, under the influence of an applied electric field X, is usually taken to be v = KX, where k is the ion mobility, expressed in centimeters-per-second per volts-per centimeter. Assuming that ions are formed at the peak of an impressed sinusoidal field, their subsequent velocity would then be

$v = k\,E\cos\omega t$, where E is the peak field strength and is 2π times the frequency. During the next quarter-cycle, until the field diminishes to zero, the ion will move a distance $x = \int_0^{\frac{\pi}{2}} v\,dt$

Or, $x = \int_0^{\frac{\pi}{2}} k\,E\cos\omega t\,dt = \dfrac{k\,E}{\omega}$ centimeters

hence $k = \dfrac{\omega x}{E} = \dfrac{2\pi f x}{E}$

Now from the curves on page 38 it can be concluded that for a 1-millimeter gap, the ions were able to reach the surface of the electrode for frequencies below about 300 kilocycles.

Assuming that the ions must traverse approximately half the total gap, x is then 0.05 centimeter. Using for E a value of 30,000 volts per centimeter, which is approximately the spark-over level, gives

$$k = \frac{2\pi \times 3 \times 10^5 \times 0.05}{30{,}000} = 3 \text{ cm/sec/volt/cm (approximately)}$$

APPENDIX B

TABULATED DATA

TESTS ON 6.25 -cm. SPHERES AT 308 KILOCYCLES

Barometer 75.10 cm, temperature 25°C.

GAP LENGTH (millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
6.25	18260	17800
"	18130	18000
"	17920	18100
"	17920	18000
"	18350	18100
5.37	15400	14800
"	15300	15000
"	15400	15100
"	15300	15000
"	15400	15000
4.83	13700	13600
"	13700	13700
"	13800	13600
"	13700	13600
"	13600	13600
4.01	12200	11800
"	12200	11800
"	12300	11700
"	12100	11800
"	12200	11800
3.04	9850	9500
"	9730	9450
"	9560	9450
"	9730	9450
"	9770	9450
2.28	7880	8000
"	8130	7900
"	8210	7900
"	8530	7900
"	8000	7900
1.63	7030	6480
"	6750	6480
"	6880	6400
"	7000	6480
"	6960	6480
0.86	4300	3900
"	4250	3900
"	4330	3850
"	4220	3900
"	4330	3900

TESTS ON 2-cm. SPHERES AT 308 KILOCYCLES

Barometer 75.93 cm, Temperature 24°C.

GAP LENGTH (millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
6.32	17800	17500
"	17800	17400
"	18000	17400
"	18200	17500
"	18100	17400
5.73	16300	16100
"	16400	16100
"	16300	16100
"	16300	16100
"	16600	16100
4.72	13600	13400
"	13800	13400
"	13800	13400
"	13800	13300
"	13800	13300
4.07	11900	11900
"	11900	11900
"	11900	11900
"	11900	11900
"	12100	19000
3.56	11000	10800
"	10900	10600
"	11200	10700
"	11000	10700
"	11000	10700
2.35	8430	8150
"	8500	8200
"	8750	8200
"	8750	8150
"	8750	8100
1.82	7620	7100
"	7820	6900
"	7500	6900
"	7300	7000
"	7500	7000

TESTS ON 2-cm. SPHERES AT 308 KILOCYCLES
(Cont'd)

GAP LENGTH (millimeters)	SPARK-OVER VOLTAGE (Peak Volts, Corrected) Not irradiated	Irradiated
1.12	5900	4800
"	4900	4800
"	5400	4750
"	5200	4700
"	5300	4700
1.65	6900	6500
"	6700	6470
"	7000	6470
"	7050	6470
"	7100	6440

TESTS ON 6.25 cm. SPHERES AT 750 KILOCYCLES

Barometer 75.00 cm., Temperature 27°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not Irradiated	Irradiated
6.45	17900	17800
"	17900	17800
"	18200	17800
"	18000	17800
"	17850	17900
4.81	13700	13600
"	13700	13540
"	13700	13540
"	13700	13540
"	13600	13540
3.49	10300	10200
"	10500	10150
"	10500	10220
"	10300	10220
"	10300	10220
2.48	7700	7600
"	8000	7700
"	8100	7750
"	8000	7700
"	8160	7700
2.08	6800	6700
"	7000	6650
"	7050	6650
"	7100	6650
"	7050	6650
1.63	6000	5750
"	6000	5700
"	6000	5700
"	5900	5650
"	5950	5650
1.07	4640	4500
"	4600	4450
"	4760	4450
"	4960	4450
"	4960	4450

TEST ON 2-cm. SPHERES AT 750 KILOCYCLES

Barometer 74.93 cm., Temperature 27°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not Irradiated	Irradiated
6.45	17900	17600
"	18300	17600
"	17900	17600
"	17900	17700
"	18300	17700
4.82	14500	13400
"	14100	13300
"	13600	13500
"	14000	13400
"	13600	13400
3.50	11100	10400
"	11200	10200
"	10800	10300
"	11000	10300
"	11200	10300
2.50	8300	7800
"	8600	7760
"	8600	7760
"	8750	7700
"	8750	7760
1.64	5820	5650
"	5950	5600
"	6760	5670
"	6480	5670
"	6480	5670
1.10	4820	4650
"	4980	4650
"	4980	4650
"	4900	4650
"	5150	4650

TESTS ON 6.25-cm. SPHERES AT 2088 KILOCYCLES

Barometer 76.20 cm., Temperature 28°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, Corrected) Not irradiated,	Irradiated
5.93	17650	16800
"	16600	17000
"	17100	16800
"	17000	16800
"	17000	17000
4.83	14000	14000
"	13700	13700
"	14000	13800
"	13500	14000
"	13600	13900
3.80	11100	11400
"	11100	11300
"	11200	11400
"	11200	11200
"	11200	11300
2.86	8800	8460
"	8600	8460
"	8600	8570
"	8550	8570
"	8400	8500
1.62	5220	5250
"	5220	5200
"	5300	5150
"	5300	5200
"	5260	5200
1.11	4280	3950
"	4030	3900
"	4030	3950
"	4030	3950
"	4030	3900

TESTS ON 2-cm. SPHERES AT 2088 KILOCYCLES

Barometer 76.94 cm., Temperature 25°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
6.00	16900	17100
"	17250	17200
"	17150	16900
"	17250	17000
"	17150	17100
4.42	13000	12800
"	12800	13000
"	13100	13100
"	12900	13200
"	13000	13100
3.77	11050	11000
"	11250	11000
"	11250	11100
"	11360	11100
"	11360	11200
2.72	8500	8450
"	8470	8380
"	8550	8380
"	8650	8380
"	8470	8380
1.63	5250	5300
"	5250	5300
"	5360	5300
"	5400	5350
"	5400	5450
0.64	3550	2970
"	3350	2970
"	3150	3000
"	3550	2970
"	3150	2970

TESTS ON 2-cm. SPHERES AT 4873 KILOCYCLES

Barometer 76.15 cm., Temperature 27 °C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
6.45	18300	18300
"	18400	18100
"	18500	18000
"	18400	18100
"	18300	18200
4.83	14150	14200
"	14250	14100
"	14150	14200
"	14450	14100
"	14350	14100
3.43	10800	10600
"	10800	10500
"	10800	10500
"	10700	10500
"	10700	10500
2.49	7800	7700
"	7760	7700
"	7760	7650
"	7760	7650
"	7760	7700
1.53	5160	5020
"	5080	5020
"	5210	4980
"	5450	4980
"	5250	4980

TESTS ON 2-cm. SPHERES AT 8015 KILOCYCLES

Barometer 77.20 cm., Temperature 28°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
4.15	12500	12400
"	12500	12500
"	12500	12500
"	12400	12500
"	12500	12500
3.06	9350	9500
"	9570	9600
"	9350	9600
"	9350	9500
"	9460	9600
2.10	6860	6800
"	6860	6800
"	6830	6740
"	6900	6800
"	6860	6800
1.13	4180	4000
"	4180	4000
"	4060	4000
"	4100	3960
"	4100	4000

TESTS ON 2-cm. SPHERES AT 12500 KILOCYCLES

Barometer 75.96 cm., Temperature 28°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
6.47	18000	17800
"	18200	17800
"	18200	17800
"	18100	17800
"	17800	17800
4.83	14150	13950
"	13700	13950
"	13900	13850
"	13900	13850
"	14150	13950
3.52	10700	10750
"	10700	10750
"	10700	10750
"	10800	10750
"	10900	10750
2.50	8240	8050
"	8360	8150
"	8360	8050
"	8330	8050
"	8240	8150
1.12	4030	4050
"	4120	4000
"	4130	4050
"	4160	4000
"	4120	4050

TESTS ON 2-cm. SPHERES (IRRADIATED)

Barometer 76.20 cm., Temperature 25°C.

GAP LENGTH 0.50 Millimeters

FREQUENCY	SPARK -OVER VOLTAGE (CORRECTED	FREQUENCY	SPARK-OVER VOLTAGE (CORRECTED)
2088 KC	2600	300 KC	2600
"	2640	"	2600
"	2600	"	2600
"	2600	"	2600
"	2600	"	2600
2 847 KC	2500	750 KC	2650
"	2500	"	2650
"	2500	"	2600
"	2500	"	2600
"	2500	"	2600
3550 KC	2350		
"	2400		
"	2400		
"	2400		
"	2350		
4873 KC	2250		
"	2250		
"	2300		
"	2300		
"	2350		
8015 KC	2250		
"	2200		
"	2200		
"	2200		
"	2150		
12500 KC	2100		
"	2100		
"	2100		
"	2100		
"	2100		

TESTS ON 2-cm. SPHERES (IRRADIATED)

Barometer 75.97 cm., Temperature 27°C.

GAP LENGTH 0.77 Millimeter

FREQUENCY	SPARK-OVER VOLTAGE (CORRECTED
300 KC	3600
"	3550
"	3550
"	3550
"	3550
500 KC	3550
"	3600
"	3550
"	3550
"	3600
750 KC	3500
"	3500
"	3500
"	3500
"	3500
2000 KC	3200
"	3200
"	3200
"	3200
"	3200

GAP LENGTH 1.60 millimeter

FREQUENCY	SPARK-OVER VOLTAGE (CORRECTED)
300 KC	6400
"	6400
400 KC	6300
"	6300
500 KC	6300
"	6250
"	6200
"	6250
"	6200
1000 KC	5500
"	5500
"	5500
"	5500
"	5450
2000 KC	5300
"	5150
"	5200
"	5150
"	5150

TESTS ON ROD GAP AT 2088 KILOCYCLES

Barometer 76.20 cm., Temperature 28°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
25.00	19000	14600
"	16300	14600
"	17300	14500
"	16500	14800
"	16900	14700
19.20	15000	13700
"	14750	13900
"	15700	13900
"	15100	13900
"	15500	13900
14.37	13900	12400
"	15300	12400
"	15000	12500
"	13700	12500
"	14300	12600
9.54	12300	11000
"	11900	11100
"	13000	11000
"	12500	11100
"	12600	11000
4.83	7800	8400
"	8500	8500
"	9020	8500
"	9430	8500
"	9210	8450
2.50	5330	5900
"	5940	5950
"	6060	5900
"	6350	5900
"	6380	5800

TESTS ON ROD GAP AT 4873 KILOCYCLES

Barometer 76.00 cm., Temperature 27°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
23.10	14250	13600
"	14350	13700
"	13800	13700
"	14500	13200
"	15000	13300
19.20	12250	12700
"	12700	12700
"	13900	12700
"	13900	12700
"	14100	12700
9.70	11200	10600
"	11400	10500
"	10700	10600
"	11500	10600
"	11300	10600
4.85	7300	7900
"	7700	8100
"	7800	8200
"	8200	8200
"	8200	8200
2.15	4260	4700
"	4260	5030
"	4230	5630
"	4430	5750
"	4300	5800
"	5640	5870
"	5830	5800

TESTS ON ROD GAP AT 8015 KILOCYCLES

Barometer 76.04 cm., Temperature 26°C.

GAP LENGTH (Millimeters)	SPARK-OVER VOLTAGE (Peak Volts, corrected) Not irradiated	Irradiated
11.65	12100	11200
"	12100	11500
"	12600	11500
"	12600	11500
"	12600	11500
9.55	10300	10500
"	12000	10500
"	12200	10700
"	11200	10500
"	11500	10500
4.88	8400	8700
"	8600	8600
"	8600	8500
"	8700	8400
"	8800	8400
2.85	6900	6600
"	7100	6700
"	7700	6500
"	7900	6700
"	7800	6700
1.63	3300	4500
"	3750	4600
"	4000	4700
"	4300	5000
"	4600	5000

CALIBRATION OF VACUUM -TUBE VOLTMETER

Cylindrical Capacitance C = 0.632 $\mu\mu$ F.

Frequency (Kilocycles)	Capacitance Current (Milliamperes)	Calculated Peak Volts	Voltmeter Reading
2760	37.0	4760	1.20
"	24.5	3160	0.80
"	30.5	3930	0.99
"	36.5	4700	1.99
2482	26.4	3770	0.95
"	34.8	4980	1.26
"	42.2	6030	1.54
"	45.2	6460	1.64
"	52.5	7510	1.88
"	53.5	7650	1.90
"	49.2	7030	1.75

Cylindrical Capacitance C = 0.885 $\mu\mu$ F.

2482	56.4	5750	1.44
"	69.5	7090	1.75
"	71.8	7320	1.82
"	74.0	7550	1.88
"	44.3	4520	1.14
"	36.5	3720	0.95
"	27.5	2800	0.72
"	47.2	4810	1.19

Cylindrical Capacitance C = 0.434 $\mu\mu$F.

2185	24.5	5800	1.42
"	28.2	6680	1.60
"	56.2	8580	2.07
"	44.4	10530	2.55
"	44.4	10530	1.00
"	50.5	12000	1.15
"	51.0	12100	1.18
"	59.8	14200	1.36
"	65.0	15400	1.48
"	69.4	16400	1.57
"	75.2	17800	1.72
"	36.5	8650	0.81
"	32.5	7700	0.72
5089	59.5	6070	1.50

CALIBRATION OF VACUUM-TUBE VOLTMETER
(Cont'd)

Cylindrical Capacitance C = 1.760 $\mu\mu$F.

Frequency (Kilocycles)	Capacitance Current (Milliamperes)	Calculated Peak Volts	Voltmeter Reading
308	27.0	11200	2.66
"	24.0	9960	2.40
"	24.5	10170	2.44
"	24.5	10170	0.96
"	24.0	9960	2.42
"	19.0	7880	1.88
"	31.5	13100	1.22
"	36.5	15100	1.43
"	20.0	8300	2.00
"	38.2	15800	1.50
"	42.3	17500	1.67
"	45.2	18700	1.78
"	31.0	12900	1.20
"	46.0	19100	1.83
"	46.2	19150	1.81
"	46.8	19400	1.84
"	46.4	19200	1.83
"	46.2	19150	1.81
"	46.0	19100	1.80
"	43.5	18000	1.73
"	42.6	17700	1.69
"	41.4	17200	1.64
"	39.8	16500	1.57
"	38.5	16000	1.52
500	33.0	8450	2.07
"	39.0	9980	2.45
"	33.8	8650	2.10
"	40.7	10400	2.53
"	22.8	5840	1.45
"	38.6	9880	0.94
"	44.4	11350	1.08
"	49.8	12750	1.22
"	55.2	14100	1.35
"	59.7	15280	1.48
"	63.4	16200	1.54

CALIBRATION OF VACUUM-TUBE VOLTMETER
(Cont'd)

Cylindrical Capacitance C = 1.760 $\mu\mu$ F.

Frequency (Kilocycles)	Capacitance Current (Milliamperes)	Calculated Peak Volts	Voltmeter Reading
900	49.0	6950	1.70
"	65.0	9220	2.25
"	32.0	4540	1.10
"	32.7	4640	1.13
"	39.0	5530	1.35
"	74.7	10600	2.62
"	74.4	10540	2.60
"	74.0	10480	1.01
"	52.2	7400	1.80
2000	67.0	4280	1.05
"	73.0	4660	1.14

DIRECT-CURRENT CALIBRATION OF THERMOCOUPLE

Western Electric Co. Thermocouple No. 21136 rated 5 ohms, 75 milliamperes, connected to General Electric Co. microammeter No. 1112211

Heater Current (Milliamperes)	Meter Reading (0-3 scale)
20.76	0.145
28.93	0.280
35.42	0.410
42.63	0.590
48.51	0.730
53.30	0.855
59.61	1.016
65.35	1.170
70.77	1.317
74.72	1.420
53.47	0.867
37.53	0.470
25.10	0.226
15.70	0.100
67.80	1.243
64.10	1.142

BIBLIOGRAPHY

1. "American Standards for Measurement of test Voltage in Dielectric Tests". Approved November 1942 by the American Standards Association. Published by the American Institute of Electrical Engineers.

2. "Dielectric Phenomena in High-Voltage Engineering". A book by F. W. Peek,Jr. Published by McGraw-Hill Book Co.

3. "The Relation Between Frequency and Spark-over Voltage in a Sphere-gap Voltmeter". by L. E. Reukema in the Transactions of the American Institute of Electrical Engineers. Volume 47, pages 38-49.

4. "The Electric Strength of Air at High Frequencies". by E. W. Seward in the Journal of the Institution of Electrical Engineers. Volume 84, February 1939, pages 288-294

5. "Radio Frequency High-Voltage Phenomena". by A. Alford and S. Pickles in the Transactions of the American Institute of Electrical Engineers. Volume 59, pages 129-136.

6. "Radio-Frequency Spark-over in Air". by P. A. Ekstrand, in Proceedings of the Institute of Radio Engineers. Volume 28, June 1940, pages 262-266.

7. "The Effects of Irradiation, Humidity, and Sphere Material on the Spark-over Voltage of the Two-Centimeter Sphere Gap". by A. B. Lewis in the Journal of Applied Physics. Volume 10, August 1939, pages 573-577.

8. "A Theoretical Determination of Breakdown Voltage for Sphere Gaps." by J. M. Meek, in the Journal of the Franklin Institute. Volume 230, August 1940, pages 229-242.

9. "Fundamental Processes of Electrical Discharge in Gases" a book by L. H. Loeb. Published by John Wiley and Sons. New York

10. "Electrical Discharges in Air at Atmospheric Pressure". by L. H. Loeb and A. F. Kip in the Journal of Applied Physics. Volume 10, March 1939, pages 141-160.

11. "A Theory of Spark Discharge" by J. M. Meek in the Physical Review, April 15, 1940, pages 722-728.

12. "The Electric Spark in Air". by J. M. Meek. in the Journal of the Institution of Electrical Engineers. Volum 89, Part I. August 1942, pages 335-356.

13. "Lowering of Spark-over Voltage by External Ionization". by C. Brinkmann in Archiv fur Elektrotechnik. Volume 33, February 15, 1939, pages 121-130.

14. "The Variation of Sparking Potential with Initial Photo-Electric Current". by J.M. Meek, in the Proceedings of the Physical Society. Volume 52. July 1940, pages 547-558 and November, 1940, pages 822-828.

15. "The Variation of Sparking Potential with Intense Ultra-Violet Illumination". by H. J. White, in the Physical Review, Volume 48, July 15, 1935, pages 113-117.

16. "The Influence of Irradiation on the Measurement of Impulse Voltages with Sphere Gaps". by J. M. Meek, in the Journal of The Institution of Electrical Engineers. Volume 93, Part 2, April 1946, pages 97-115.

17. "The Calibration of 2-cm. Diameter Sphere Gaps". by R. Cooper, D.E.M. Garfitt, and J.M.Meek in the Journal of the Institution of Electrical Engineers. Volume 95, Part 2, June 1948. pages 309-311.

18. "Oscillographic observations on Ultra-High-Frequency Sparks". by W.A. Prouse and W. Jasinski. in Nature, January 15, 1949, pages 103-104.

19. "The Space Charge Due to Corona". by O.J.M. Smith in the Transactions of The American Institute of Electrical Engineers. Volume 67, 1948, Part II. pages 1137-1144.

20. "The Electrical Breakdown Strength of Air at Ultra-High Frequencies". by J. A. Pim, in the Proceedings of the Institution of Electrical Engineers. Volume 96, Part II. March 1949, pages 117-129.

21. "Limits for the Diffusion Theory of High Frequency Gas Discharge Breakdown". by S. C. Brown and A.D. MacDonald, in the Physical Review, December 1, 1949, pages 1629-1633.

22. "High Frequency Gas Discharge Breakdown in Hydrogen", by A.D. MacDonald and S.C.Brown, in the Physical Review, December 1, 1949, pages 1634-1639.

23. "Experiments on the Electric Strength of Air at Centimeter Wavelength" by R. Cooper, in The Journal of the Institution of Electrical Engineers, 94 part III, September 1947, pages 315-324.

24. "The Microwave Spark" by D. Q. Posin, in The Physical Review. Volume 75. March 1, 1948, pages 496-509.

25. "The Breakdown of Gases in High Frequency Electric Fields" by D. H. Hale in The Physical Review, Volume 73, May 1, 1948, pages 1046-1052.

26. "Oscillations in Ionized Gases" by Lewi Tonks and Irving Langmuir in The Physical Review, volume 33. February 1929, pages 195-210.

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